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X-RAY OBSERVATIONS OF THE BRIGHT SEYFERT GALAXY IC 4329A

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ABSTRACT

We have performed a detailed analysis of the broad-band (0.1–25 keV) *EXOSAT* observations of the high-luminosity, nearby Seyfert type I galaxy IC 4329A. The observations were carried out on two occasions, 1984 July and 1985 July. The X-ray luminosity decreased by ~35% over one year. A significant short-term variability where the intensity decreased by ~12% on a time scale of $\sim 2 \times 10^4$ s was detected in the 1985 data. The observed X-ray spectra are all well fitted by simple power-law models with nearly 10 times larger absorption than the Galactic value, indicating significant absorbing matter local to the source, consistent with the reddening observed in the optical spectrum. We do not find any evidence for low-energy excess in the spectra. The photon index Γ is measured to be 1.85 ± 0.06 (90% confidence) in 1984 and $1.77^{+0.06}_{-0.05}$ (90% confidence) in 1985. We find a Fe line emission at 6.4 keV with an equivalent width of 169^{+124}_{-113} eV in the 1984 data when the source was bright. The results are used to constrain the mass of the putative supermassive black hole in the nucleus of IC 4329A. The implications of the results on the matter surrounding the active galactic nucleus in IC 4329A are discussed.

Subject headings: galaxies: individual (IC 4329A) — galaxies: Seyfert — galaxies: X-rays — X-rays: spectra

1. INTRODUCTION

The edge-on spiral (Sa) galaxy with a prominent dust lane bisecting its nucleus, IC 4329A, is a Seyfert type I galaxy at a redshift of 0.0157 (Disney 1973; Wilson & Penston 1979). It belongs to a poor cluster of galaxies (richness class 0) and is ~3′ away from the giant elliptical galaxy IC 4329, the brightest (optical) galaxy in the cluster (Sandage 1975; Daly, Phillipps, & Disney 1987). It has extreme Seyfert I characteristics, very broad Hα line emission, and highly reddened nucleus (Disney 1973; Wilson & Penston 1979). The luminosity of its dereddened nucleus ($M_V = -23.0$–-25.3) is comparable to that of a QSO. It is also a very strong infrared source (Ward et al. 1987). Radio emission from IC 4329A has been reported by Unger et al. (1987).

X-Ray emission from the Seyfert galaxy IC 4329A was discovered with the *Ariel V* satellite (Elvis et al. 1978; McHardy et al. 1981). The identification of X-ray emission with the galaxy was made unambiguous by observations with the rotation modulation collimator aboard the *SAS 3* satellite (Delvaille, Geller, & Schnopper 1978). The *SAS 3* observations required that either the X-ray source is extended or there is another source in the neighborhood. The source has also been observed with *HEAO 1* (Dower et al. 1980; Piccinotti et al. 1982; Tennant & Mushotzky 1983), *Einstein Observatory* (Petre et al. 1984; Holt et al. 1989), *Tenma* (Miyoshi et al. 1988), *EXOSAT* (Turner & Pounds 1989), and *Ginga* (Piro, Yamauchi, & Matsuoka 1990). The 2–10 keV X-ray flux of IC 4329A has been found to be highly variable over a time scale of 1 yr (Marshall, Warwick, & Pounds 1981). Measurements with the *Ariel 5* from ≃4 yr of observations when combined with those of the *SAS 3* and the *HEAO 1* show that its flux varies in the range $(4.0–13.0) \times 10^{-11}$ ergs cm^{-2} s^{-1} (Marshall et al. 1981). Tennant & Mushotzky (1983) did not find any variability on hourly time scales during the pointed mode observations using the *HEAO 1* lasting for 6 hr. A few days later, however, the source was found to be ~40% brighter in the *HEAO 1* scanning observations (Piccinotti et al. 1982), indicating variability on a time scale of days.

The X-ray source is highly absorbed, and an equivalent hydrogen column density $N_{\rm H}$ of $(4.4 \pm 0.4) \times 10^{21}$ has been measured with the Solid State Spectrometer (SSS) and the Monitor Proportional Counter (MPC) aboard the *Einstein Observatory* (Holt et al. 1989). No low-energy excess was found in these observations. Recent observations with the *Ginga* satellite, however, required a partial covering model for the spectral fitting which indicates a low-energy excess. The *EXOSAT* observations showed a peculiar excess in one of the filters used for the low-energy detector, which could not be spectrally modeled (Turner & Pounds 1989).

The X-ray spectrum of IC 4329A has been well represented by a power law with the photon index (Γ) in the range of 1.6–1.7, in measurements reported prior to the *Ginga* observations. *Ginga* measured the value of Γ to be 1.85 ± 0.02. A very hard X-ray tail above 10 keV has been reported by Miyoshi et al. (1988) from observations with *Tenma*. The *Ginga* observations confirmed the presence of a hard bump above 8 keV in the X-ray spectrum. The measurements with *Ginga* also showed the presence of a fluorescence line due to iron at 6.4 keV (Piro et al. 1990). The line was not detected in the *Tenma* observations.

The source was observed with the *EXOSAT* satellite on two occasions, once in 1984 and once in 1985. Results from only the 1984 observations have been reported by Turner & Pounds (1989). We have carried out a detailed analysis (including reanalysis of the already analyzed data) of the archival data from both the *EXOSAT* observations, and we present our results here. In particular we have looked for (1) X-ray variability on long and short time scales, (2) presence of any low-energy excess and the peculiar low-energy excess reported in the earlier *EXOSAT* observations, (3) presence of line features and spectral hardening, and (4) the dependence of spectral parameters on the intensity states of the source. The previous analysis of 1984 observations did not address the above issues in detail.

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The paper is organized as follows. In § 2 we give the details of the two observations. In § 3 we present the variability and spectral analysis of the low-energy and the medium-energy data and the results obtained. We discuss the results in § 4, ending with conclusions.

2. OBSERVATIONS

The X-ray observations were performed on 1984 July 19/20 and 1985 July 31, using both the medium-energy (ME) detectors and the low-energy (LE) telescope having a channel multiplier array (CMA) as the detector. The ME argon- and xenon-filled proportional counters are sensitive to X-rays in the energy range of 1–25 keV, whereas the LE+CMA combination detects softer X-rays in the energy range of 0.1–2.0 keV. The details of the instruments used are given by Turner, Smith, & Zimmermann (1981) for the ME detectors and by de Korte et al. (1981) for the LE+CMA. The LE and ME data were obtained simultaneously.

The LE data were obtained employing three broad-band filters in front of the CMA, viz., Lexan 3000 (LX3), aluminum/Parylene (Al/P), and boron (BOR) (see White & Peacock 1988 for filter efficiencies). The times of observations and the effective exposure times with each filter are given in Table 1.

The ME data were acquired from eight argon- (Ar) filled detectors as well as from the eight xenon- (Xe) filled detectors. These detectors are divided into two half-arrays, viz., the detector numbers 1, 2, 3, and 4 collectively known as the half-1 array and the other four detectors (numbers 5, 6, 7, and 8) collectively known as the half-2 array. The ME observations were carried out by alternately pointing one of the arrays at the source while the other array monitored the background, using the "swap" technique (Smith 1984). The observation times and the useful exposure times with each half-array on the source are given in Table 1.

3. ANALYSIS AND RESULTS

The data reduction and analysis were performed using the XANADU (X-ray Analysis and Data Utilization) software package.

TABLE 1

LOG OF *EXOSAT* OBSERVATIONS OF IC 4329A AND THE COUNT RATES

Detector Combination	Start Time (UT)	End Time (UT)	Effective Exposure Time (s)	Count Rate[a] (10^{-4} cm^{-2} s^{-1})
		1984 Jul 19/20		
CMA+LX3	23:53:16	01:31:16	5539	4.6 ± 0.4
CMA+Al/P	01:34:36	03:21:08	6206	3.4 ± 0.3
CMA+BOR	03:24:12	05:54:20	8678	2.8 ± 0.3
ME (Half-1)	23:31:24	02:46:20	10398	124.6 ± 1.1
ME (Half-2)	02:59:48	05:58:36	7912	120.5 ± 1.0
		1985 Jul 31		
CMA+LX3	13:51:48	15:19:24	5256	3.7 ± 0.4
CMA+LX3	22:01:56	22:36:20	2048	3.6 ± 0.6
CMA+Al/P	15:24:12	17:07:03	6176	3.2 ± 0.4
CMA+BOR	17:11:24	21:58:12	17200	1.6 ± 0.2
ME (Half-2)	13:09:48	15:01:56	6728	80.6 ± 0.9
ME (Half-1)	15:18:36	18:07:08	10112	80.9 ± 0.7
ME (Half-2)	18:26:04	22:46:12	15992	70.7 ± 0.7

[a] The count rates for the ME argon detectors are for PHA channels 7 to 24 corresponding to the energy range of 1.5–6.0 keV with the best signal-to-noise ratio.

3.1. *LE Data*

Soft X-ray emission from a point source coinciding with the optical position of IC 4329A was detected in all the filters and on all occasions. The background-subtracted source count rates corrected for vignetting, telemetry dead time, and the sum-signal distribution are listed in Table 1 for all the filters used. The errors quoted in Table 1 are of 1 σ confidence level. The background was obtained from regions surrounding and adjacent to the position of the source. We used the cell size of 128×128 arcsec^2 for source detection. The background was determined from 4 times bigger area. No extended emission was detected from the Seyfert galaxy or the regions surrounding it. We also looked for X-ray emission from the giant elliptical IC 4329 in the field of view but failed to detect it.

The count rates obtained with the BOR filter from IC 4329A show a clear variability over a time scale of 1 yr. Although a similar trend can be seen with the other filters, the variability in the LX3 and Al/P count rates is not significant due to large error bars resulting from shorter exposure times with these two filters. The discrepancy in the decrease of the boron count rate with respect to the other filters is significant at only 1.7 σ level. Search for variability on time scales shorter than 10^4 s did not yield anything significant with any of the filters. The LE source counts (bin size = 500 s) from the observation in 1985 are shown in Figure 1, for comparison with the ME count rates which showed rapid variability (see below).

3.2. *ME Data*

The ME data were analyzed using the background obtained from the same detectors while offset. The count rates detected from IC 4329A are given in Table 1, after correcting for vignetting and dead time. The source is very strong in the ME and shows a clear decline ($\sim$35%) in intensity over a time scale of 1 yr, consistent with the BOR count rates. The data were also analyzed for variability on shorter time scales ($\sim 10^3$–10^4 s). No such variability was detected during the 1984 observations [χ^2 per degree of freedom (dof) < 1 for a constant source hypothesis]. The ME count rate measurements in 1984 (see Table 1) with the half-1 and half-2 detectors seem to show a small drop ($\sim$3%), which appears significant with respect to the statistical errors quoted. This small variation is, however, attributed to the small differences in the spectral response of the two halves. The spectral analysis of the two halves separately did not show any such variation. The observations in 1985, however, show a significant short-term variability as can be seen from Figure 1 where we display the 1985 ME data using a bin size of 500 s. The simultaneously obtained background, which is found to be steady, is also shown in Figure 1. The source count rate decreased by $\sim$12% from the beginning to the end of observations in 1985 showing variability on a time scale of $\sim 2 \times 10^4$ s. The significance of this decrease, observed with the same half, is borne out by the following analysis.

The observations in 1985 were taken with both the ME halves as shown in Table 1, that is, half-2 followed by half-1 which in turn was followed by half-2 again. None of the three continuous observations with a given half showed a significant variability as checked by the χ^2 statistic for the hypothesis of constancy. The values of χ^2 obtained from the hypothesis of a constant rate as given by the average during the observation are given in Table 2 along with associated probabilities and the average values for each half. The average source intensity is constant from UT 13:00 to 18:00, in half-2 and half-1, whereas it is $\sim$12% lower after 18:26 in half-2. The analysis of the

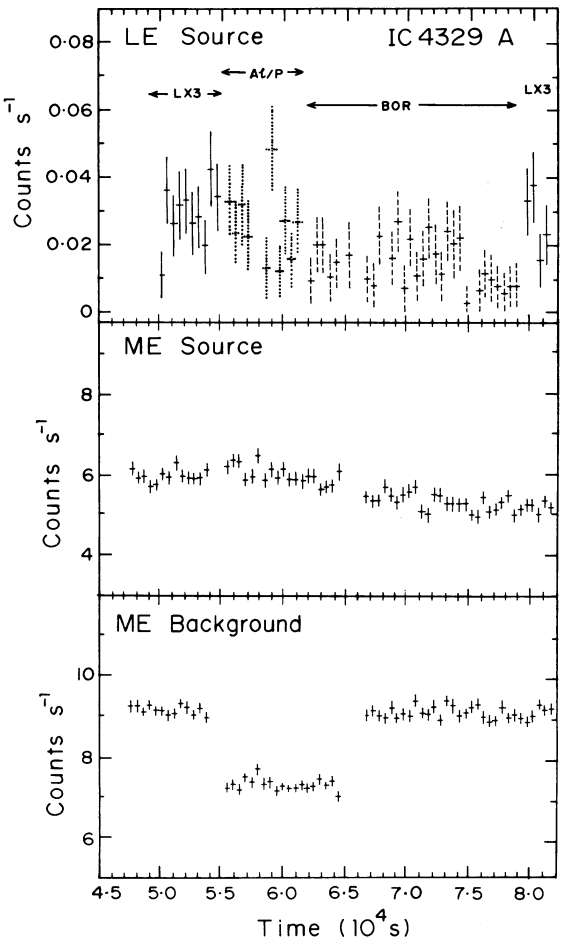

FIG. 1.—Background-subtracted LE and the ME *EXOSAT* source counts detected on 1985 July 31 from IC 4329A are shown with a bin size of 500 s. Time is in UT seconds on 1985 July 31. LE filters used for the different parts of the data are indicated. Simultaneously monitored ME background count rates and the ME half-array used are also shown in the figure.

combined data from all the halves shows that the significance of the variability is very high based on the χ^2 test for a constant source hypothesis ($\chi^2 = 362.3$ for 62 dof). Even if the data from half-2 alone are considered, that is at the beginning and at the end of observation, the value of χ^2 obtained is 226.3 for 43 dof for a constant source. We have tried to model the intensity variation by adding a linear term to a constant term and used the χ^2 statistic to determine the goodness of fit. The results of this modeling are also shown in Table 2. The addition of a linear term significantly improved the fit to the data from half-2 ($\chi^2 = 51$ for 42 dof). There is only a marginal indication for source variability on time scales shorter than 10^4 s after 18:26 UT. A search for periodicity in the variations did not give any positive results.

Although the ME count rates indicate an almost continuously varying trend, the data can be roughly divided into two states, *high* before UT 18:00 and *low* after 18:26, and they nearly coincide with a filter change in the LE and a swap of the ME array.

3.3. *Spectral Analysis*

The pulse-height (PH) data obtained from the LE and the ME detectors (Ar and Xe) were analyzed together to study the X-ray spectrum of IC 4329A. To study the spectral variations in the source, we have analyzed separately three sets of data. The 1984 data, when the source was at its brightest in the present observations, are analyzed separately. The source was fainter by ~35% in 1985, and the data are divided into two intensity states (see above) and analyzed independently. We examined PH data from each ME detector individually for any systematics arising from background subtraction. The spectra were examined visually for proper background subtraction at high energies where the charge particle contributions can be significant. A simple power law was also used, and the resultant fits were verified for mutual consistency and acceptable χ^2_{min}. Detectors which gave discrepant results or an unacceptably high χ^2_{min} were not used. The detectors thus selected for the analysis are given in Table 3. The selected detectors are in the corner configuration and are known to be the most reliable ones (Izzo & Parmar 1986; Yaqoob, Warwick, & Pounds 1989). The spectral parameters were estimated by performing a simultaneous fit to LE data and the PH data from the selected Ar and Xe detectors. The ME detectors were later grouped together, Ar and Xe separately, for plotting purposes only. This avoids systematic errors of combining different detectors before the analysis.

We used simple power-law and thermal bremsstrahlung models along with absorption in the line-of-sight to fit the data. The absorption cross sections given by Morrison & McCammon (1983) were used. Using the χ^2 statistic we find that these simple models give acceptable fits. The power-law models are, however, strongly preferred over the thermal bremsstrahlung. For example, the thermal model for the low-intensity state in 1985 can be rejected with a confidence of

TABLE 2

RESULTS OF THE ANALYSIS OF X-RAY LIGHT CURVE[a] OF IC 4329A AS OBSERVED ON 1985 JUL 31

Time (UT)	ME Half	Model[b]	Best-Fit Parameters: a	Best-Fit Parameters: b	DOF	χ^2	Probability of ($>\chi^2$)
13:10–15:02.........	2	Constant	6.0	...	12	11.6	0.478
15:19–18:07.........	1	Constant	6.0	...	18	28.6	0.054
18:26–22:46.........	2	Constant	5.3	...	30	46.7	0.027
13:10–22:46.........	Both	Constant	5.6	...	62	362.3	0.0
13:10–22:46.........	2	Constant	5.5	...	43	226.3	0.0
13:10–22:26.........	2	Linear	7.4	-2.9×10^{-5}	42	51.0	0.16

[a] Energy range is 1.5–6.0 keV, and the bin size is 500 s.

[b] The constant model a is in counts s^{-1}, and the linear model is of the type $a + bt$, where t is the time and b is in counts s^{-2}.

TABLE 3

ME DETECTORS[a] SELECTED FOR SPECTRAL ANALYSIS

	1984 JUL 19/20	1985 JUL 31 13:00–18:00	1985 JUL 31 18:26–22:46
Argon	1, 5, 8	1, 4, 5, 8	5, 8
Xenon	1, 4, 5, 8	1, 8	5, 8

[a] Indicated by numbers in the table.

$>99\%$. The estimated spectral parameters are given in Table 4, for the fitted models. The 90% confidence error bars for a given parameter were computed by keeping all the other parameters free (χ^2_{min} + 4.61 for two free parameters). The 2–10 keV fluxes observed from IC 4329A are also given in Table 4. The spectral data from the 1984 observations are shown in Figure 2. The best-fit power law model convolved with the detector response is shown as a histogram. The residuals between the data and the model are shown in the lower panel of the figure. A positive excess near 6 keV can be seen quite clearly in the residuals.

On all occasions the absorption column density is found to be considerably higher than the Galactic absorption in the line-of-sight measured from 21 cm observations. The Galactic absorption in the direction of IC 4329A is 4.55×10^{20} (Elvis, Lockman, & Wilkes 1989). The total absorption is nearly 10 times higher, indicating absorption local to the source. The estimated absorption is consistent with the previous measurements (see § 4).

Line features in the X-ray spectrum of IC 4329A have recently been reported by Piro et al. (1990). We examined the data for evidence of line emission by adding to the continuum models, a Gaussian with a fixed width of 0.1 keV and a variable line energy. A very significant reduction in the χ^2 was obtained by this addition to the 1984 data. The $\Delta\chi^2 \geq 10.4$ justifies the presence of line emission with a confidence $>99.9\%$ using the F-statistic. The best-fit value for line energy is 6.4 keV, and its equivalent width is measured to be 169^{+124}_{-113} eV. The line flux is measured to be $(2.7 \pm 1.8) \times 10^{-4}$ photons cm^{-2} s^{-1}. Figure 3 shows the 1984 measurement of PH data and a histogram of the best-fit power-law with Gaussian model convolved with the detector response. The residuals between the data and the model are displayed in the lower panel of the figure. The allowed values of the line energy and line intensity are shown in Figure 4 for different levels of confidence. The contours plotted in Figure 4 are for χ^2_{min} plus 2.71, 4.61, and 9.21 corresponding to confidence levels of 67%, 90%, and 99%, respectively, for two parameters of interest. No significant improvement in the fit was obtained when a Gaussian was added to the spectral data obtained in 1985. An upper limit of 2.2×10^{-4} photons cm^{-2} s^{-1} (90% confidence) is obtained for the line flux from the 1985 data. This corresponds to an upper limit of 150 eV for the equivalent width of the line.

We have also investigated if there are any long-term spectral changes associated with the intensity variation. The allowed ranges for the two interesting parameters, N_H and Γ, are shown in Figure 5 for the 1984 data and the high-intensity state of 1985. The contours displayed enclose the allowed parameter space with the confidence associated with χ^2_{min} plus 2.71, 4.61,

TABLE 4

RESULTS OF THE SPECTRAL ANALYSIS OF *EXOSAT* LE AND ME DATA ON IC 4329A

PARAMETER	DATE OF OBSERVATION 1984 Jul 19/20	1985 Jul 31 13:00–18:00	1985 Jul 31 18:26–22:46
Model 1—Power Law and Absorption			
Photon index (Γ)	1.81 ± 0.05	$1.77^{+0.06}_{-0.05}$	1.82 ± 0.09
A (10^{-2} cm^{-2} s^{-1} keV^{-1})	$4.7^{+0.35}_{-0.30}$	$2.9^{+0.25}_{-0.2}$	$2.8^{+0.4}_{-0.3}$
N_H (10^{21} cm^{-2})	$4.7^{+0.7}_{-0.6}$	$3.3^{+0.8}_{-0.6}$	$4.5^{+1.7}_{-1.2}$
χ^2/dof	346.1/382	373.4/337	255.8/226
Model 2—Power Law and Gaussian Line and Absorption			
Photon index (Γ)	1.85 ± 0.06	...	...
A (10^{-2} cm^{-2} s^{-1} keV^{-1})	$4.9^{+0.4}_{-0.3}$	...	...
E_{line} (keV)	6.4 ± 0.6	...	...
A_{line} (10^{-4} cm^{-2} s^{-1})	2.7 ± 1.8	...	...
N_H (10^{21} cm^{-2})	$4.9^{+0.8}_{-0.7}$	...	...
χ^2/dof	335.7/380	...	...
Model 3—Thermal Bremsstrahlung and Absorption			
kT (keV)	$10.1^{+1.1}_{-0.9}$	$10.3^{+1.3}_{-1.2}$	$9.9^{+2.0}_{-1.6}$
A (10^{-2} cm^{-2} s^{-1} keV^{-1})	1.39 ± 0.10	$0.88^{+0.08}_{-0.07}$	$0.82^{+0.12}_{-0.10}$
N_H (10^{21} cm^{-2})	$2.8^{+0.5}_{-0.4}$	2.0 ± 0.5	$2.3^{+1.0}_{-0.7}$
χ^2/dof	364/382	394/337	281/226
Flux (2–10 keV) (10^{-11} ergs cm^{-2} s^{-1})	15.5	10.1	9.10

NOTE.—Quoted errors are at the 90% confidence level (χ^2_{min} + 4.61 for two free parameters) computed while keeping the rest of the variables as free parameters.

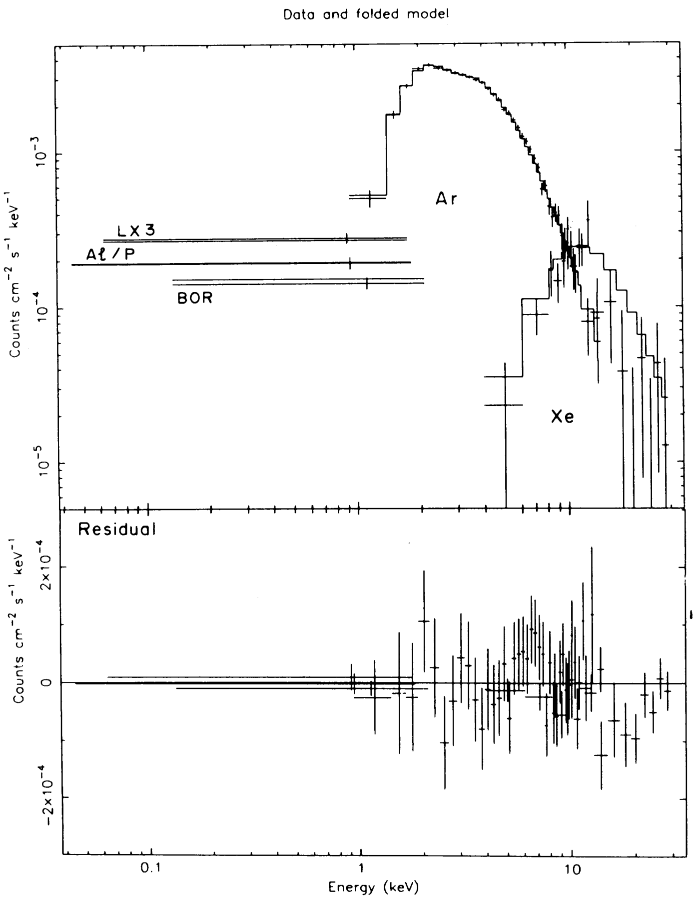

FIG. 2.—X-Ray spectrum observed with the LE and ME detectors of *EXOSAT* on 1984 July 19–20 is shown. LE filters used for the observations are indicated. Histogram shows the predicted count distribution from the best-fit single power-law spectrum with low-energy absorption. Lower panel shows the residuals between the data and the best-fit model. An excess near 6 keV can be seen clearly.

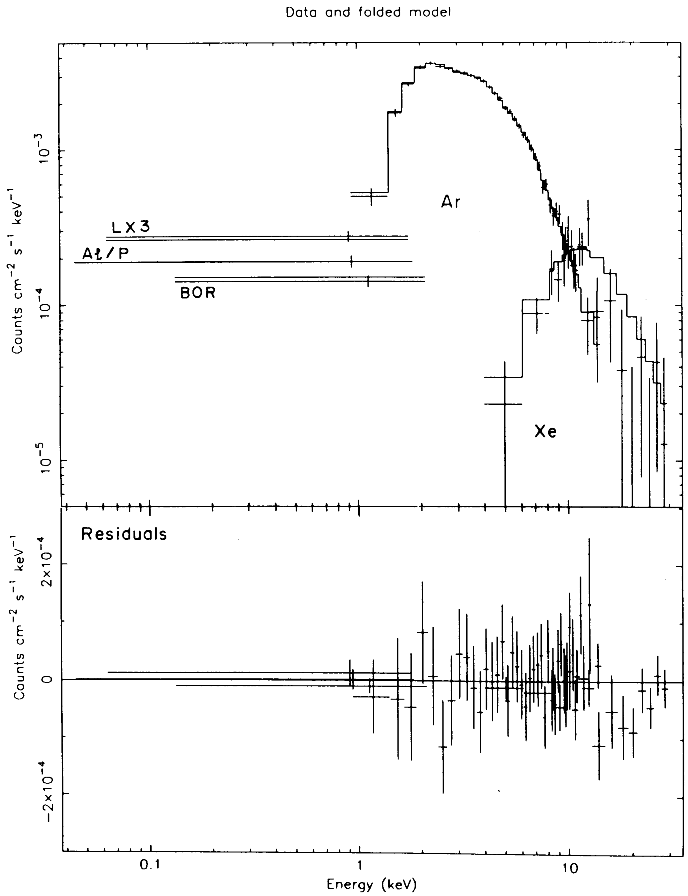

FIG. 3.—X-Ray spectral data is the same as in Fig. 2. The histogram shown, however, includes a Gaussian line in addition to the power-law model. Lower panel shows the residuals as before.

and 9.21. It is observed that at 90% confidence level ($\chi^2_{\rm min} + 4.61$) the two spectral parameters have changed, with the brighter state in 1984 showing slightly higher Γ and higher $N_{\rm H}$. The allowed range for the low intensity in 1985 spans both the regions shown in Figure 5 and is not shown for clarity.

We also tried fitting the partial covering models and found essentially the same results as from the fully covered model used above. We, therefore, feel that the partial-covering models are not required by the present data. We have carefully looked for soft excess in the data by examining the residuals from the best-fit model and find no evidence for the existence of any low-energy excess.

4. DISCUSSION

4.1. *Comparison with the Previous Analysis*

In a study of X-ray spectra of a large number of Seyfert galaxies, Turner & Pounds (1989) reported on the 1984 *EXOSAT* observations. Their spectral fit to the LE + ME data by a simple power law was rather poor, and the resultant fit statistically unacceptable ($\chi^2_\nu = 2.21$ for 35 dof; probability $< 5 \times 10^{-5}$). This was purported to be mainly due to an excess in the count rate observed with the boron filter. We have examined the LE count rates observed with each filter, in detail, by

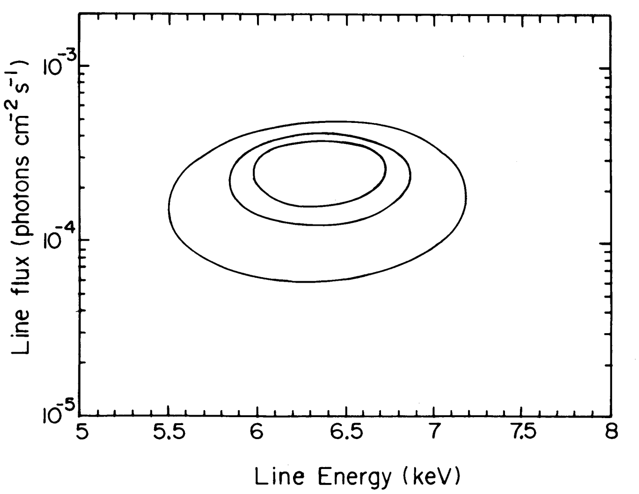

FIG. 4.—Contours enclosing the allowed range of the 6.4 keV line (modeled as a Gaussian) flux and the line energy are shown for different confidence levels. (from *EXOSAT* 1984). Three contours are for $\chi^2_{\rm min}$ plus 2.71, 4.61, and 9.21 corresponding to confidence levels of 67%, 90%, and 99%, respectively, for two parameters of interest.

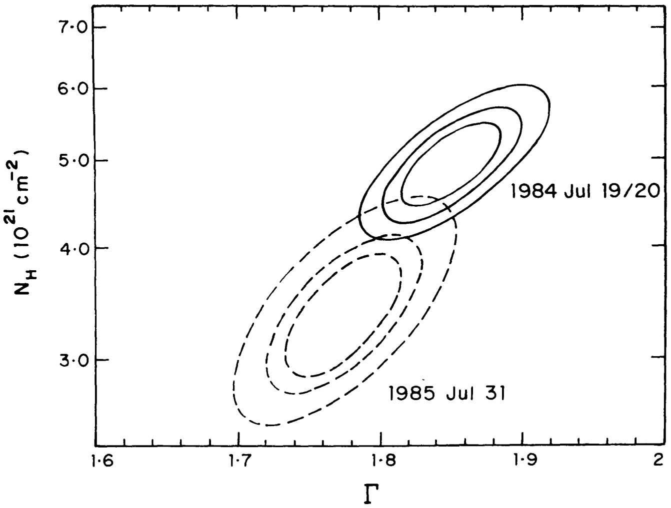

FIG. 5.—Contour diagram of the allowed ranges of the Γ and N_H for the *EXOSAT* 1984 spectral data and the 1985 high-state spectral data. Three contours are shown for each of the two observations. Confidence levels associated with the contours are the same as in Fig. 4.

studying the effect of different sizes of boxes used for obtaining the count rates. The count rates reported by us in Table 1 are for the optimum box size beyond which any further increase in the size has no effect. The count rates so derived by us for the LX3 and Al/P and given in Table 1 are in agreement with those reported by Turner and Pounds. The boron count rates are, however, significantly lower than those reported earlier. The earlier analysis utilized a fixed box size of 100 × 100 $arcsec^2$ and a correction factor of 47% to the count rate to account for scattering in the boron filter. The point spread function of the boron filter, is, however, strongly dependent on the spectral shape and N_H, and a constant correction factor may not be applicable for all the sources, in particular for the highly absorbed sources like IC 4329A (Davelaar & Giommi 1985). Using the above box size and the correction factor, we obtain the same boron count rate as Turner and Pounds. Our analysis of the combined LE + ME PH data results in exceedingly good fit by simple power-law models (see Figs. 2 and 3 and Table 3) and we don't find any discrepancy due to the boron filter rate. The resultant best-fit spectral parameters differ slightly but significantly from those of Turner and Pounds. We believe that the spectral parameters reported here are more accurate (see also § 4.4 below).

The spectral results from the 1985 data are presented here for the first time. The boron filter was used in this observation also. Following the same procedure, as above, for the analysis of the combined LE + ME data for the two intensity states of the source again resulted in a good fit to simple power-law models (see Table 4), and no discrepancy was found due to the boron filter rates.

4.2. *Short-Term X-Ray Variability*

The most important result of the present analysis is the detection of a significant short-term ($\sim 2 \times 10^4$ s) variability in the X-ray emission from IC 4329A in the 1985 observation. X-ray emission from AGNs and their variability are normally believed to be due to the release of gravitational energy from the infall of matter onto a supermassive black hole (SMBH). The variability time scale can be used to estimate the efficiency of conversion of matter to radiation via accretion on a SMBH. Following the prescription of Fabian (1979) that the efficiency η should exceed 5×10^{-42} $\Delta L/\Delta t$ results in $\eta > 0.003$ for the observed $\Delta t = 2 \times 10^4$ s. Under the assumption that the X-ray emission originates from a region of ~ 5 Schwarzschild radii (Shapiro, Lightman, & Eardley 1976), the mass of the SMBH can be limited to be smaller than 2×10^4 Δt $M_\odot$. This gives an upper limit of 4×10^8 $M_\odot$. This derivation assumes that the size of the region responsible for the variable component is the same as that of the total X-ray emission, that is, 5 Schwarzschild radii. Considering that the variability amplitude is only 12%, this component could arise from a smaller region, for example, a hot spot in the accretion disk of size *f* Schwarzschild radii, and consequently the upper limit on the mass of the SMBH will be higher by a factor 5/*f*.

The X-ray luminosity of IC 4329A as observed with *EXOSAT* in the 2–10 keV bandwidth is in the range 1–1.7 × 10^{44} ergs s^{-1}, assuming a distance of 94.9 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1}; $q_0 = 0$) for the source. If the spectrum observed in 1984 is extrapolated over the energy range of 0.1–100 keV (assuming no internal absorption in the source), the X-ray luminosity can be as high as 7.4×10^{44} ergs s^{-1}. Considering further the luminosity of the source in radio (Unger et al. 1987), infrared (Ward et al. 1987), and optical (Wilson & Penston 1979), the bolometric luminosity (radio to X-ray) of the "core" in IC 4329A could easily be 10^{45} ergs s^{-1}. In order that this luminosity does not exceed the Eddington luminosity, the mass of the SMBH must be at least 8×10^6 $M_\odot$. If the total nuclear luminosity is released with an efficiency of 0.003, it would require an accretion rate of ~ 6 $M_\odot$ yr^{-1}.

4.3. *Long-Term X-Ray Variability*

A 35% variation in one year has been very clearly detected in the observations presented here. It is instructive to compare this with X-ray intensity measurements from different experiments. In Table 5 we have compiled the 2–10 keV X-ray intensity of IC 4329A as observed over the years using different satellites. Data in this table have been collected from observations with *SAS 3*, *Ariel 5*, *HEAO 1*, *HEAO 2*, *Tenma*, *EXOSAT*, and *Ginga* satellites spanning a period 1974–1989 (references are in the table). It is evident from the table that the variability is common in IC 4329A. A factor of 3–4 variability is observed over the years. On a time scale of ~1 yr, however, a variation amplitude of ~30%–40% appears to be common. The *HEAO 1* saw no short-term variability during a few hours of pointing (Tennant & Mushotzky 1983), but in the scans on the days just before and after the pointing, the average X-ray intensity seems to have been almost 40% higher. Variability of ~30%–40% in the intensity, therefore, appears to occur on a time scale of a day also.

4.4. *X-Ray Spectrum*

In Table 5 we have also compiled a summary of the spectral parameters measured for IC 4329A. The present observations confirm the presence of a large amount of absorption of soft X-rays. The only accurate measurement of N_H reported prior to this analysis was based on the SSS observations (Petre et al. 1984; Holt et al. 1989). The agreement between the values of the column density derived here and the earlier measurement is remarkable. These values are also in agreement with the reddening observed in the optical (Wilson & Penston 1979;

TABLE 5

SUMMARY OF X-RAY OBSERVATIONS OF IC 4329A

Date	Observatory	Flux (2–10 keV) (10^{-11} ergs cm^{-2} s^{-1})	Photon Index (Γ)	N_H (10^{21} cm^{-2})	Reference
1974 Oct–1979	*Ariel 5*	6.0 to 13.0	...	...	Marshall et al. 1981
1976 Jun	*SAS 3*	10.0	...	...	Delvaille et al. 1978
1978 Jan 23–29	*HEAO 1* (A2)	7.7 ± 0.4	...	...	Piccinotti et al. 1982
1978 Jul 27	*HEAO 1* (A2)	5.1	$1.56^{+0.06}_{-0.11}$	<18.0	Tennant & Mushotzky 1983; Mushotzky 1983
1978 Jul 27	*HEAO 1* (A3)	4.0 ± 0.4	...	...	Dower et al. 1980
1978 Jul 27–Aug 1	*HEAO 1* (A2)	7.2 ± 0.8	...	...	Piccinotti et al. 1982
1979 Aug 11	*Einstein* (MPC)	12.65	1.68 ± 0.05	...	Petre et al. 1984
1979 Aug 11	*Einstein* (SSS)	...	$1.82^{+0.19}_{-0.10}$	5.3 ± 1.1	Petre et al. 1984
1979 Aug 11	*Einstein* (SSS+MPC)	12.0	1.60 ± 0.06	4.4 ± 0.4	Holt et al. 1989
1984 May 31–Jun 5	*Tenma*	13.8 ± 0.8	1.63 ± 0.05	<5.6	Miyoshi et al. 1988
1984 Jul 20	*EXOSAT* (LE+ME)	15.5 ± 0.1	1.85 ± 0.06	$4.9^{+0.8}_{-0.7}$	Present work
1985 Jul 31 (13:00–18:00)	*EXOSAT* (LE+ME)	10.1 ± 0.1	$1.77^{+0.06}_{-0.05}$	$3.3^{+0.8}_{-0.6}$	Present work
1985 Jul 31 (18:26–22:46)	*EXOSAT* (LE+ME)	9.1 ± 0.1	1.82 ± 0.09	$4.5^{+1.65}_{-1.24}$	Present work
1989 Jul 8	*Ginga*	13.8	1.85 ± 0.02[a]	$2.6^{+0.7}_{-0.6}$[a]	Piro et al. 1990

[a] Based on partial covering model.

Pastoriza 1979). The value of observed reddening, A_V, is in the range 2.5–4.8 mag and corresponds to a hydrogen column density of (4.9–9.4) $\times 10^{21}$ atoms cm^{-2} assuming the relations $A_V = 3.0E_{B-V}$, where E_{B-V} is the color excess and $N_H \simeq 5.9 \times 10^{21} E_{B-V}$ (Burstein & Heiles 1978). The lower value of the reddening seems to be favored by the X-ray data.

Variable absorption has been seen in some AGNs, viz., MR 2251-178 (Halpern 1984; Pan, Stewart, & Pounds 1990) and NGC 4151 (Yaqoob et al. 1989), and has been explained by invoking the warm absorber models (Halpern 1984). There is an indication of variability, on a time scale of a year, of the column density in IC 4329A in the present observations (see Fig. 5). The N_H measured with *Ginga* is in fact nearly 50% lower than the *EXOSAT* and *Einstein* measurements (see Table 5), confirming the variability of N_H. No significant trend with the X-ray intensity is, however, visible from the global data in Table 5. Further, confirmation of variable absorption with better observations in the future is extremely important to study the effect of intense X-ray emission on the absorber surrounding the source.

The spectral index, Γ, is found to be 1.85 ± 0.06 from the 1984 observations with the best statistics. It lies in a broader range of 1.72–1.91 in the 1985 observations when the source intensity was low. Considering that the canonical Seyfert spectrum is 1.67 with an intrinsic scatter of only 0.15 (Rothschild et al. 1983; Mushotzky 1983), it appears that the spectral slope of 1.85 ± 0.06 determined for IC 4329A deviates toward an extreme in the "canonical spectrum" scenario. The present determination is definitely steeper than the *HEAO 1*, *Tenma*, and *Einstein* (see Table 5 for the results of joint analysis of SSS and MPC data reported by Holt et al. 1989) measurements ($\Gamma \simeq 1.6$) but consistent with the recent *Ginga* measurements using the partial-covering models. Although the *EXOSAT* data seems to suggest a steepening of Γ with intensity (see Fig. 5), this does not appear to be the overall trend when all the previous measurements are also taken into account. Similar trends have, however, been seen in other Seyfert galaxies, for example, 3C 120 (Halpern 1985), NGC 5548 (Branduardi-Raymont 1986), NGC 4051, (Lawrence et al. 1985; Matsuoka et al. 1990), MCG -6-30-15 (Matsuoka et al. 1990), NGC 4151 (Yaqoob & Warwick 1989), and Mrk 509 (Singh et al. 1990).

We detect significant line emission centered at 6.4 keV, when the source was at its brightest state in the present observations. The uncertainty in the line energy, however, does not allow us to distinguish between the two possible origins of the line emission, viz., fluorescence of cold iron in the neighborhood of the AGN or ionized iron in a hot thin plasma. The equivalent width of the line (169^{+124}_{-113} eV) is observed to be consistent with the measurement of 100 ± 20 eV reported by Piro et al. (1990) from *Ginga* observations. The line was not detected with *Tenma* which had better energy resolution detectors (Miyoshi et al. 1988). The 2 σ upper limit on the equivalent width reported by them, was, however, 480 eV. The X-ray intensity during the *Ginga* and *Tenma* observations was only slightly lower ($\simeq$10%) than during the 1984 *EXOSAT* observations, whereas it was considerably lower ($\simeq$35%) during the 1985 *EXOSAT* observations when we failed to detect any significant line feature. The 90% upper limit to the line flux in the 1985 observations is, however, consistent with the line flux detected in the 1984 observations. Therefore, there is no evidence for variability in the line flux. The X-ray intensity was even lower during the previous observations with *HEAO 1* and *Einstein* (see Table 5) from which no line detection has been reported. The lack of variability in the line flux in the present observations makes it possible for it to originate from a hot gas in an extended region. The absence of soft excess, however, limits the extent of such a region to be smaller than the size of the absorbers, which do vary on a $\sim$1 yr time scale. In this context observations with better statistical precision to study the line variability would be extremely useful.

The *Ginga* and *Tenma* observations have also reported the detection of a high-energy bump in the X-ray spectrum of IC 4329A. We have looked for a similar tail in the *EXOSAT* data. We fail to detect a hard bump in the *EXOSAT* data. The

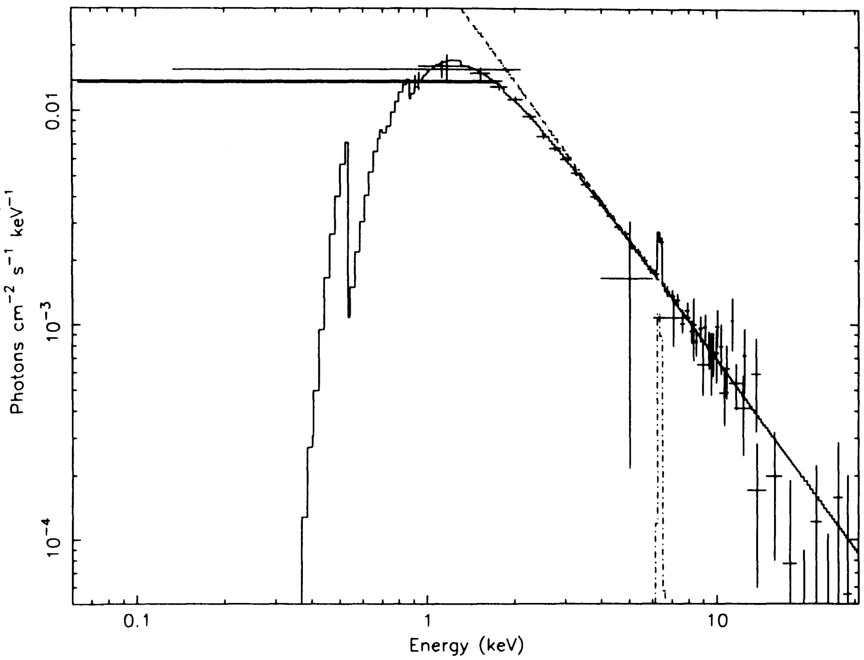

FIG. 6.—Unfolded photon spectrum observed in 1984 (*EXOSAT*) is shown for comparison with the *Ginga* and *Tenma* spectra. Source intensity was higher in this observation than in the *Ginga* and *Tenma* observations.

detection efficiency of the *EXOSAT* ME detectors for energies >8 keV, however, compares rather poorly with that of the *Ginga* Large Area Counters (LAC). In Figure 6 we show the unfolded X-ray spectrum of IC 4329A as observed in 1984 for comparison with a similar figure in Piro et al. (1990). The error bars at the high-energy end of Figure 6 can easily accommodate a hard bump of intensity reported by Piro et al. Therefore we do not rule out the existence of a hard bump in the X-ray spectrum of IC 4329A. The hard tail reported from the *Tenma* observations is, however, too strong to have been missed in the present observations.

The observed line emission can perhaps be best explained by the fluorescence of iron from an accretion disk surrounding the SMBH (George, Nandra, & Fabian 1990). The existence of a hard bump as observed with *Ginga* has lent further support to this scenario (Piro et al. 1990). Observations of correlated variability of the hard bump and that of the line emission would be extremely useful for understanding the environs of the AGN in IC 4329A.

In conclusion, a detailed analysis of two *EXOSAT* observations of the Seyfert galaxy IC 4329A has revealed long-term and short-term X-ray intensity variations. Intensity variations by ~35% on a time scale of 1 yr and ~12% on a time scale of about 2×10^4 s are detected. The observed X-ray spectra are well fitted by simple power-law models without any indication for low-energy excess. The observed value of N_H, (2.7–5.7) $\times 10^{21}$ cm^{-2} s^{-1}, is nearly 10 times larger absorption than the Galactic value, implying the presence of considerable absorption local to the source and consistent with the reddening observed in the optical spectrum. The photon index Γ lies in the range 1.7–1.9 with an evidence for variability at 90% confidence level. Line emission at 6.4 keV, presumably due to the fluorescence of Fe, is detected in one of the observations when the source was bright. The observed short-term variability and luminosity (1) constrain the mass of the assumed SMBH in IC 4329A to lie in the range 8×10^6–$4 \times 10^8\ M_\odot$, (2) require the conversion efficiency of matter to radiation to be greater than 0.003, and (3) require an accretion rate of $\sim 6\ M_\odot$ yr^{-1}. The large equivalent width (169^{+124}_{-113} eV) of the Fe fluorescence line requires the surrounding matter to subtend a large solid angle.

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