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EXOSAT OBSERVATIONS OF THE SEYFERT 1 GALAXY NGC 3516

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ABSTRACT

Results of the X-ray spectra (0.1–10 keV) of the Seyfert galaxy NGC 3516 are presented based on the *EXOSAT* observations obtained on four epochs between 1985/308 and 1985/340. The data were obtained from the *EXOSAT* archives. The soft X-ray (0.1–2 keV) flux of this galaxy varied by a factor of ~3 on the time scales of 2 days, and that for the hard X-ray (2–10 keV) flux varied by a factor of ~1.5 over the period of a month. The observed spectra are best fitted by a power-law, uniform absorption, and a Gaussian line model. Best-fit parameters of this model suggest that NGC 3516 is a flat spectrum source. Weak soft excess and significant intrinsic absorption ($N_H \sim 10^{22}$ cm^{-2}) have been detected in the spectrum of this galaxy. An emission line detected with a high significance (>99.9%) around 6.0 keV could be the redshifted 6.4 keV iron line due to the fluorescence of thick cold iron present around the nucleus of NGC 3516 or due to the red-shifted 6.7 keV helium-like iron line produced in an optically thin hot plasma of temperature around $\sim 10^8$ K. Measured equivalent width of the line ranges between 106 and 1240 eV. A very interesting feature of this line is that it has displayed very broad (~1.0 keV) line width which may be the first observational result on the broadening of the Fe K-shell lines in an AGN, NGC 3516.

Subject headings: galaxies: individual (NGC 3516) — galaxies: Seyfert — galaxies: X-rays — radiation mechanisms

1. INTRODUCTION

NGC 3516 (UGC 6153, MCG +12-11-009) is an original Seyfert galaxy (Seyfert 1943) which has been classified as RSBO type galaxy with heliocentric radial velocity as 2664 ± 22 km s^{-1} (Sandage & Tammann 1981). The apparent magnitude of this galaxy is 12.40 in the V band ($B-V = 0.72$, $U-B = -0.23$), and its absolute magnitude is -21.2 ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, and an optical spectral index α equal to 0.7) with $z = 0.009$ (Adams 1977; Osterbrock 1977; de Vaucouleurs & de Vaucouleurs 1968).

Results of optical (Boksenberg & Netzer 1977) and *IUE* ultraviolet (Ulrich & Boisson 1983; Ulrich 1986; Voit, Shull, & Begelman 1987) spectrophotometry have shown that this galaxy displays remarkable variability in the nuclear continuum and nuclear emission lines on time scales of days, weeks, and months which are commonly found in the spectra of Seyfert type I galaxies. On the basis of long-slit spectroscopic observations, Ulrich & Pequignot (1980) concluded that the gas motions outside the nucleus could not be explained by normal rotation of the galaxy. They suggested that the ionized gas seen at several kiloparsecs from the center has been thrown by the nucleus or the nuclear radiation had ionized and accelerated circumnuclear gas. Recently, Goad & Gallagher (1987) have carried out high-resolution (6.7 Å mm^{-1}) long-slit echelle spectroscopic observations, and they have found that the spatially extended circumnuclear emission-line region shows an anomalous velocity which was previously suggested by Ulrich & Pequignot (1980). Goad & Gallagher have suggested a low-velocity, bipolar outflow (from the nucleus) model to explain the kinematics of circumnuclear gas in NGC 3516 which was later supported by Pogge (1989). Radio observations at 2, 6, and 20 cm have revealed a weak and unresolved source which coincides with the nucleus of NGC 3516 (Ulvestad & Wilson 1984, 1989 and references therein). This galaxy was also observed with the *IRAS* satellite (IRAS 11033+7250), and far-infrared emissions have been detected in it at 12, 25, 60, and 100 μm, and the IR continuum flux increases with wavelength (see Kim 1989 for detail references).

Many observations have been carried out for NGC 3516 in the ultraviolet, optical, and radio wavelengths but it has not been studied well in X-rays. This galaxy was observed in 1979 with the *Einstein Observatory* Imaging Proportional Counter, and it displayed X-ray (0.2–3.5 keV range) flux variations by a factor of 3.2 over a time scale of 5 months (Maccacaro, Garilli, & Mereghetti 1987). However, to the best knowledge of the authors, no spectral information (2–10 keV range) is available in the literature on this galaxy, except the results published by Ku (1980). This motivated us to search the *EXOSAT* archives, and we obtained four spectra of this galaxy based on four 1985 observations by G. A. Reichert with *EXOSAT*. In this paper we present the results of the detailed spectral analysis of NGC 3516; these will be the first spectra (0.1–10 keV) of this galaxy.

2. OBSERVATIONS

Low Energy (LE) and Medium Energy (ME) detectors which were sensitive in the 0.1–2 keV and 2–10 keV range, respectively, were used during the *EXOSAT* observations (detailed information on *EXOSAT* instrumentation can be found in White & Peacock 1988). Lexan 3000 (LX3) and aluminum/Parylene (Al/P) filters were used for LE observations of NGC 3516; the details of these detectors have been described by de Korte et al. (1981). Background-subtracted LE count rates with errors were obtained from the *EXOSAT* data base; they were converted into LE pulse height (PHA) spectra using the XANADU (X-ray Analysis and Data Utilisation) software package.

Eight argon-filled proportional counters (each counter will be referred to as a "detector") were used to obtain the Medium Energy (ME) spectra (Turner, Smith, & Zimmermann 1981 have described the details of ME detectors). Those detectors were divided into two parallel rows of four detectors (half 1 and half 2 which can be either aligned to the pointing axis or

TABLE 1

LOG OF OBSERVATION OF THE LE AND ME SPECTRA AND COUNT RATES OF NGC 3516

Start Time[a] (1985)	End Time[a] (1985)	LE Count Rate LX3 (10^{-5} cm^{-2} s^{-1})	LE Count Rate Al/P (10^{-5} cm^{-2} s^{-1})	ME Count Rate[b] (10^{-3} cm^{-2} s^{-1})
308, 21:00	309, 07:25	6.15 ± 1.10	3.53 ± 0.75	1.48 ± 0.04
311, 16:56	312, 03:55	4.70 ± 0.75	3.07 ± 0.85	1.46 ± 0.03
330, 12:05	330, 19:10	4.47 ± 0.68	...	1.37 ± 0.05
340, 15:46	341, 11:03	4.43 ± 1.50	...	0.92 ± 0.03

[a] Format: day, hour:minutes.

[b] The count rates are for PHA channels 6–35 corresponding to the energy range 2–10 keV with the best signal-to-noise ratio. Detector 3 was off during ME observations.

offset by up to 2° to obtain background emissions). To remove the effects of the correlated background variability between the two halves, a "swap" technique (Smith 1984; White & Peacock 1988; Yaqoob, Warwick, & Pounds 1989) was used for background subtraction of the ME spectra. The background spectra obtained from the offset detectors are different from the corresponding background spectra of the same detectors when they are aligned. Necessary corrections were applied to the background spectra using the "difference spectra" obtained from the *EXOSAT Observatory*. Also, background variability studies were carried out and were corrected following the method described by Morini, Lipani, & Molteni (1987). Finally the corrected background spectra were subtracted from the on-source spectra to obtain the source spectra only. The above-mentioned background subtraction analysis of the four ME spectra of NGC 3516 which are presented in this paper were carried out at the *EXOSAT Observatory*. A log of LE and ME observations and count rates of NGC 3516 are presented in Table 1, and the LE and ME count rates are plotted in Figure 1.

3. ANALYSIS AND RESULTS

Analysis of the combined LE and ME spectra of NGC 3516 were carried out using XSPEC (X-Ray Spectral Fitting) software package. Four LE + ME spectra of this galaxy were analyzed separately to avoid systematic effects due to background variations and possible source variations. A simple power-law model with uniform absorption (using the absorption cross sections given by Morrison & McCammon 1983) in the line of sight to the source was used to fit the four spectra. Table 2A presents the best-fit parameters of the above model along with the 90% confidence error bars which were computed for each parameter keeping the rest of the parameters free following the procedure detailed by Lampton, Margon, & Bowyer (1976) ($\chi^2_{\rm min} + 4.61$ for two free parameters). Table 2A and Figure 2 show that this galaxy displayed soft X-ray (0.1–2 keV) flux variation by a factor of ~ 3 on a time scale of 2 days and the hard X-ray (2–10 keV) flux of this source varied by a factor of ~ 1.5 over a period of a month. However, considering the 90% error bars, the values of the spectral index, $\alpha = (\Gamma - 1)$, indicate that there were, practically, no changes of α of NGC 3516 during the *EXOSAT* observations. Values of the column densities of the equivalent hydrogen ($N_{\rm H}$) along the line of sight of NGC 3516 which are presented in Table 2A suggest that the average $N_{\rm H}$ value is greater (by two orders of magnitude) than the galactic column density value (3×10^{20} cm^{-2}; Stark et al. 1991). This means that probably there is a significant absorption in this galaxy. But our results do not show any variation of $N_{\rm H}$. In Figure 3, we show the observed LE + ME spectra of NGC 3516 with the best-fit power law with uniform absorber model convolved through the detector response, and the lower panels of these two figures show the

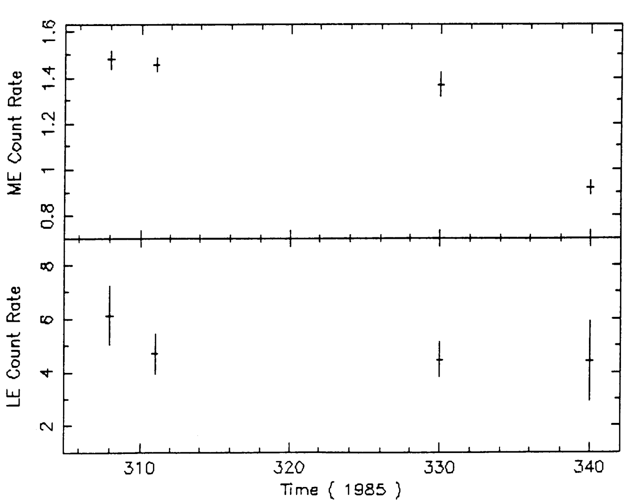

FIG. 1.—Plot of the LE and ME count rates vs. date of observations

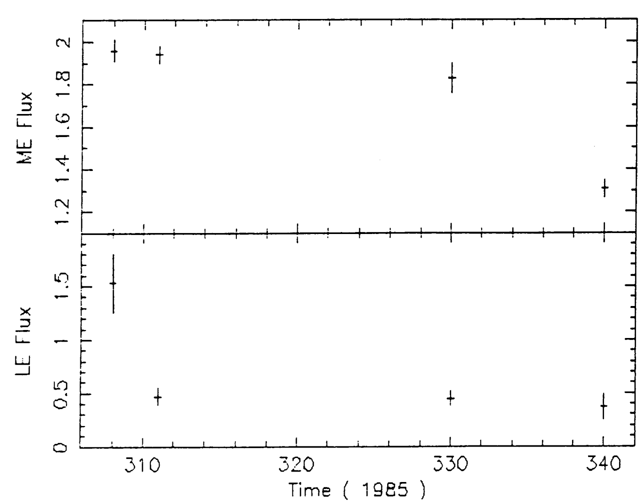

FIG. 2.—Same as Fig. 1 but for LE and ME fluxes

TABLE 2A

SPECTRAL FITS TO THE SPECTRA OF NGC 3516: POWER LAW + ABSORPTION

				FLUX		L_x[f]		
DATE (1985)	Γ[a]	N[b]	N_H[c]	0.1–2[d] (keV)	2–10[e] (keV)	0.1–2 (keV)	2–10 (keV)	χ^2_{red}/d.o.f.
308.........	1.33	2.83	1.07	1.53 ± 0.27	1.96 ± 0.05	0.57 ± 0.10	7.30 ± 0.19	2.88/28
311.........	1.32	3.08	2.82	0.47 ± 0.08	1.94 ± 0.04	0.18 ± 0.03	7.20 ± 0.15	2.31/29
330.........	1.14	2.07	2.39	0.45 ± 0.07	1.83 ± 0.07	0.17 ± 0.03	6.80 ± 0.26	2.55/30
340.........	$1.18^{+0.32}_{-0.30}$	$1.60^{+1.49}_{-0.66}$	$2.28^{+1.49}_{-1.31}$	0.37 ± 0.12	1.31 ± 0.04	0.14 ± 0.04	4.90 ± 0.15	1.43/27

[a] Photon index.
[b] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV.
[c] Column density in 10^{22} cm^{-2}.
[d] Flux in 10^{-12} ergs cm^{-2} s^{-1}.
[e] Flux in 10^{-11} ergs cm^{-2} s^{-1}.
[f] Luminosity in 10^{42} ergs s^{-1}.

residuals between the spectra and the model. From the residuals of Figure 3*b*, it can be seen that this galaxy displays weak soft excess in its spectrum. Weak soft excesses have also been detected in the spectra of this source which were observed on 1985/311 and 1985/330. However, no variations of the soft excesses were found in this source from the *EXOSAT* observations. Different models (two power laws, broken power-law, and thermal bremsstrahlung models) were used to fit the soft excess detected in this galaxy. But there were no improvements in the χ^2 statistics than that obtained from the simple power-law and uniform absorption model.

Recent results obtained from *EXOSAT* and *Ginga* (Nandra et al. 1989; Leighly, Pounds, & Turner 1989; Piro, Yamauchi, & Matsuoka 1990; Pounds et al. 1989 and references therein) show the evidences for the presence of iron K-shell emission and absorption in the X-ray spectra of Seyfert galaxies and quasars. Presence of an emission feature around 6.0 keV is also clearly evident from the residuals, presented in the lower panels of Figures 3*a*–3*b*. Also the χ^2_{red} statistics (see Table 2A) show that the simple power-law model does not provide good fits to the spectra. Therefore, a Gaussian line feature with a variable line width and line center was added with the power-law model and were fitted with the spectra. The χ^2_{red} statistics suggest that there were positive improvements in the fits over the power-law model. But the values of the line widths were very large (~2.6 keV), and the model became insensitive to compute the 90% confidence error bars. Next, we fitted the spectra using the above model with fixed line width whose values were varied between 0.1 and 1.5 keV, and we obtained a very good fit for all the four spectra with the line width value as 1.0 keV. The best-fit parameters with 90% confidence error bars are presented in Table 2B. After the addition of the Gaussian line feature around 6.0 keV, a very significant reduction in χ^2_{red} ($\Delta\chi^2 > 10$ for all the spectra) was obtained which provides a very high

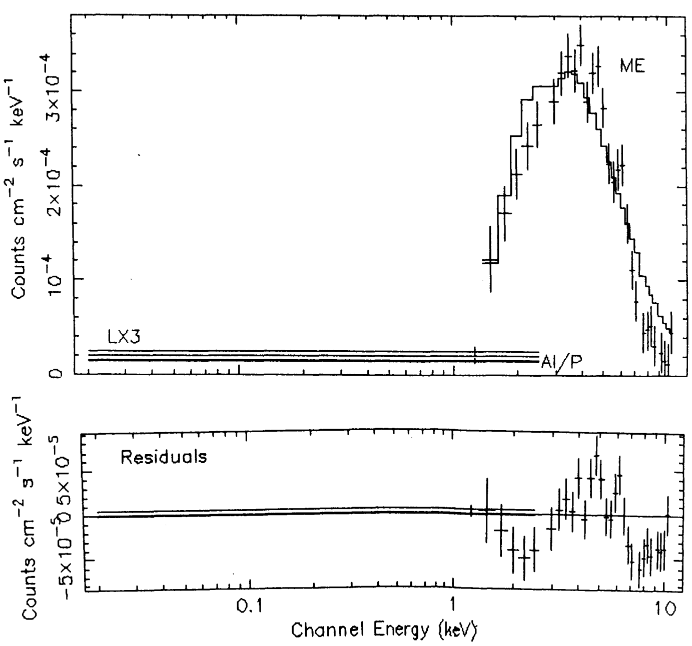

FIG. 3*a*

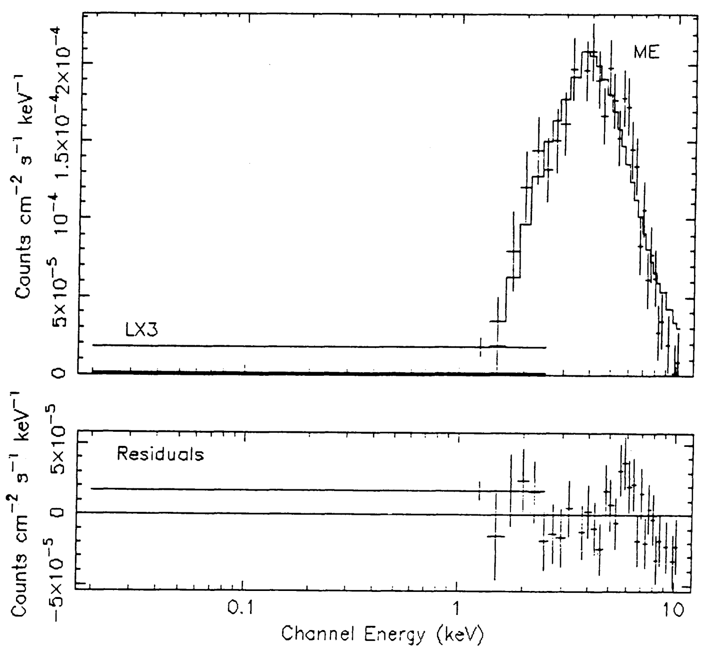

FIG. 3*b*

FIG. 3.—Observed spectrum of NGC 3516 for (*a*) 1985/308. (*b*) 1985/340 fitted with a simple power law and uniform absorption model. Lower panel of each figure shows the residuals between the spectra and the model in units of counts.

TABLE 2B

SPECTRAL FITS TO THE SPECTRA OF NGC 3516: POWER LAW + ABSORPTION + GAUSSIAN LINE

Date (1985)	Γ[a]	N[b]	N_H[c]	E_L[d]	E_N[e]	EW[f]	χ^2_{red}/d.o.f.
308.........	$1.61^{+0.40}_{-0.28}$	$3.36^{+1.83}_{-1.13}$	$1.07^{+1.10}_{-0.51}$	$5.05^{+0.32}_{-0.25}$	$2.76^{+0.78}_{-0.77}$	678 ± 189	1.08/26
311.........	$1.33^{+0.49}_{-0.41}$	$2.75^{+2.21}_{-1.96}$	$2.42^{+1.94}_{-1.38}$	$5.06^{+0.59}_{-0.51}$	$1.61^{+1.24}_{-1.21}$	424 ± 318	1.58/27
330.........	$1.36^{+1.36}_{-0.47}$	$2.42^{+3.14}_{-1.71}$	$2.15^{+1.89}_{-1.43}$	$5.95^{+0.51}_{-0.48}$	$2.65^{+1.23}_{-1.21}$	852 ± 389	1.47/28
340.........	$1.63^{+0.61}_{-0.49}$	$2.65^{+4.60}_{-1.98}$	$2.60^{+2.00}_{-1.73}$	$5.98^{+0.38}_{-0.41}$	$1.84^{+0.80}_{-0.80}$	758 ± 330	0.91/25

[a] Photon index.
[b] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV.
[c] Column density in 10^{22} cm^{-2}.
[d] Line energy in keV.
[e] Line intensity in 10^{-4} photons cm^{-2} s^{-1}.
[f] Equivalent width in eV.

significance (>99.9%) for justifying the presence of the line using the F-statistic. The value of the line center energy is best estimated to be $5.51^{+0.45}_{-0.41}$ (mean value obtained from the results of the four spectra) which may be due to the 6.4 or 6.7 keV redshifted line from iron. The equivalent width of the iron line ranges between 106 and 1240 eV which is very high if it is the 6.4 keV redshifted fluorescent iron line. The range of values for the equivalent width mentioned above takes into account only the statistical errors. LE + ME spectra, shown earlier, with the best-fit model (power-law + absorption + Gaussian line) convolved through the detector response are shown in Figure 4. Residuals between the spectra and the model are shown in the lower panels of Figures 4a and 4b. From the residuals of Figure 3a it appears that there are two emission features at 5 and 6 keV and an absorption feature at 7 keV. Dominance of the emission feature at 5 keV is doubtful and that at 6 keV is most probably due to the iron line. The absorption feature at 7 keV is, probably, due to an absorption edge which has been detected in the X-ray spectra of many Seyfert galaxies (Leighly et al. 1989). The emission feature at 5 keV may be due to the uncertainty of the data and the possibility of some miscorrection of the background. However, repeated background subtraction analysis provided the same results. If this feature is real, then the two emission features (at 5 and 6 keV) give an indication of a double-peak structure of the iron line around 6 keV which suggests the presence of an accretion disk around the central compact object.

4. DISCUSSION

The soft (0.1–2 keV) X-ray luminosity of NGC 3516, which was measured with the *EXOSAT* on four epochs in 1985, varied by a factor of ~3 on the time scale of 2 days and that for the hard (2–10 keV) X-ray luminosity varied from (7.3 ± 0.2) × 10^{42} ergs s^{-1} to (4.9 ± 0.1) × 10^{42} ergs s^{-1}

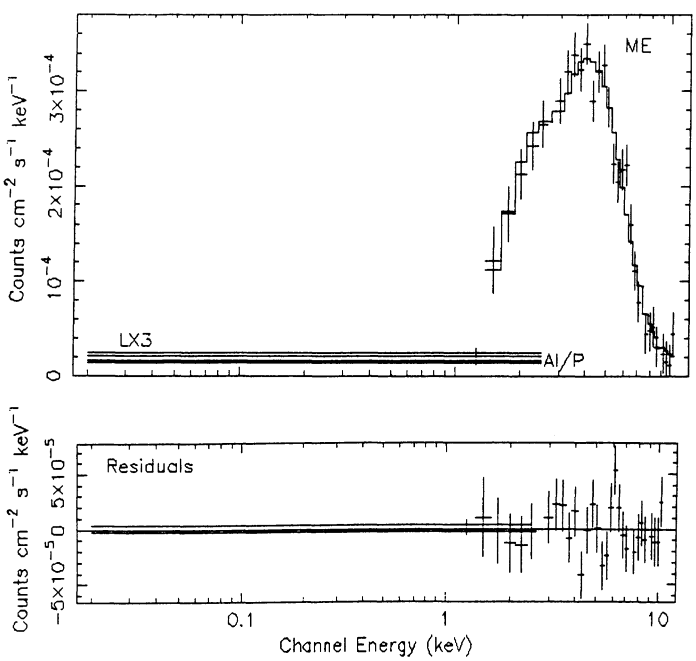

FIG. 4a

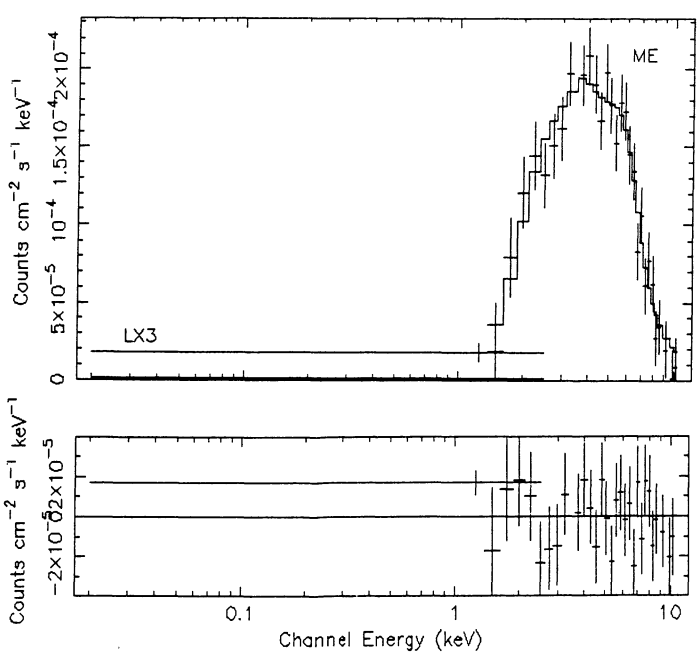

FIG. 4b

FIG. 4.—Observed spectrum of NGC 3516 for (a) 1985/308, (b) 1985/340 fitted with power law, uniform absorption, and Gaussian line model. Residuals between the spectra and the model are shown in the lower panel.

($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$) (variation by a factor of 1.5) over the period of a month. Almost same type of variation (on the time scales of months) by a factor of 3.2 in the X-ray (0.2–3.5 keV) luminosity of this source was also observed from *Einstein* IPC observations (Maccacaro, et al. 1987). However, the X-ray (0.2–3.5 keV) luminosity of this source as measured in 1979 with the *Einstein* IPC was around 3.98×10^{42} ergs s^{-1} (Halpern 1982) and that measured with *EXOSAT* in 1985 was $(2.02 \pm 0.13) \times 10^{42}$ ergs s^{-1} which shows that there was no dramatic long-term variation of this galaxy in the 0.2–3.5 keV band. But from the comparison of the luminosity values obtained from *HEAO 1* A-2, *Einstein* MPC and IPC/HRI (see Persic et al. 1989 for detailed references), and *EXOSAT* observations, it is clearly evident that this galaxy displayed strong variations of hard (2–10 keV) X-ray luminosity on time scales of years.

From the comparisons of the spectral index values presented in Tables 2A and 2B, it is clearly evident that the values of α are greater with the Gaussian line model than that obtained from the simple power-law model. The same type of spectral steepening has already been observed in many Seyferts (Piro et al. 1990; Matsuoka et al. 1990; Morisawa et al. 1990), but the cause of such spectral steepening is not known.

On the basis of optical (Goad & Gallagher 1987) and ultraviolet (Voit et al. 1987) observations, it has been suggested that the absorbing material is flowing outward from the nucleus of NGC 3516. It has also been found that the broad absorption lines at C IV λ1550, N V λ1240, and Si IV λ1400 were variable (Voit et al. 1987). From X-ray observations we also find that there is a significant absorption ($N_{\rm H} \sim 10^{22}$ cm^{-2}) at low energies in this galaxy. This type of absorption can be explained if it is due to broad-line clouds along the line of sight, and the expected column densities through such a cloud will be around $\sim 10^{22}$–10^{23} cm^{-2} (Kwan & Krolik 1981; Ferland & Mushotzky 1982; Petre et al. 1984; Reichert et al. 1985; Reichert, Mushotzky, & Holt 1986) which is consistent with the measured values of $N_{\rm H}$ for NGC 3516. However, from the present data (see Table 2A and 2B), we could not detect any variable low-energy absorption in this galaxy.

From the measured line energy ($5.51^{+0.45}_{-0.41}$), it is not possible to find out whether the observed emission line is due to the redshifted 6.4 keV fluorescent iron line or the helium-like 6.7 keV iron line. If the line has to form due to fluorescence from the thick cold matter around the central source, the equivalent width of the line has to be extremely smaller (~ 100 eV) than the observed values. The large equivalent width of the emission line can be explained if it is the 6.7 keV helium-like iron K-shell line formed in an optically thin hot plasma of a temperature about 10^8 K. But from the spectral analysis, we find that the thermal bremsstrahlung model did not provide a good fit to the X-ray spectra. The reason for the measured large equivalent width of the emission line around 6 keV is as follows: To measure a line of equivalent width betwen 100 and 200 eV, the source flux at the line energy would have to be larger than $\sim 5 \times 10^{-4}$ photons cm^{-2} s^{-1} keV^{-1} (Leighly et al. 1989). This is not true for the spectra of NGC 3516 obtained with *EXOSAT* which means that the measured values of the equivalent width of the emission line is larger. Thus we suggest that the detected emission line may be due to the fluorescence of the redshifted 6.4 keV cold iron from an accretion disk around the central continuum source. Though the majority of the X-ray astronomers have attributed this line, in the X-ray spectra of Seyfert galaxies, as being due to the redshifted fluorescent 6.4 keV line, recently Yamauchi et al. (1990) have detected the 6.7 keV helium-like iron near the Galactic center.

Repeated and careful spectral analysis show that the best fits to the spectra were obtained from a composite model consisting of a power law, uniform absorption, and a Gaussian line feature around 6.4 keV. Using the above model but with variable line width (0.1–1.5 keV), we tried to fit the spectra, and the best fit was obtained with 1.0 keV line width. Therefore, we want to emphasize that the results of the spectral analysis of NGC 3516 have displayed the evidence of a broad iron line of width 1.0 keV. This type of broad iron line around 6.4 keV has been observed in a number of bright X-ray binaries containing a black hole (Barr, White, & Page 1985; van der Woerd, White, & Kahn 1989). However, direct evidence for broadening in the Fe K-shell lines observed from AGNs is still lacking. A broad (width $\sim 1.$ keV) Fe line, around 6.0 keV, detected in the X-ray spectra of NGC 3516 is due neither to blending of differnt lines from different ionization stages of iron nor to the Compton broadening. It is suggested that the detected broad line is primarily due to the bulk plasma motions in a Keplerian disk irradiated with X-rays emitted near the central collapsed object (Kallman & White 1989; Fabian et al. 1989). Thus the detection of the broad iron line suggests the presence of a massive black hole at the center of the Seyfert galaxy NGC 3516.

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