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THE X-RAY SPECTRUM (0.1–10 keV) OF THE BROAD LINE RADIO GALAXY: 3C 390.3

K. K. GHOSH AND S. SOUNDARARAJAPERUMAL
Indian Institute of Astrophysics, Vainu Bappu Observatory, Kavalur, Alangayam, N. A., T. N., 635701, India

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ABSTRACT

Broad line radio galaxy, 3C 390.3, was observed with *EXOSAT* on several occassions between 1984 and 1986 using the low (LE) and medium (ME) energy detectors. Detailed results of the spectral analysis of the LE (0.1–2 keV) and ME (2–10 keV) spectra which were obtained from the *EXOSAT* archives, of this source are presented. Simple power law and uniform absorption model provided good fit to the combined LE and ME spectra but the hydrogen column density ($N_{\rm H}$) values are much smaller than the galactic $N_{\rm H}$ value. However, the above model with the fixed $N_{\rm H}$ value also provides good fit to the datasets. The observed x-ray spectrum is best fit by a power law of a photon index, Γ, of 1.63 ± 0.07 (error bars are with 90% confidence). Only the 2–10 keV flux shows a weak change ($\sim 25\%$) over a year and, practically, no changes were observed in the low energy flux. Weak soft excess below 2 keV was detected in this galaxy. Two power law models fit well with the data, but these models become insensitive to change to the fit parameters. Best fit results of the broken power law model which shows a slight improvement in the $\chi^2_{\rm red}$ values over the single power law model, suggests that two power law components are required to explain the x-ray spectrum of 3C 390.3. A highly significant ($> 99.9\%$) Gaussian line feature around 5.80 keV was detected which could be the redshifted 6.4 keV due to the fluorecsence of cold iron from an optically thick accretion disk around the central nonthermal x-ray source.

1. INTRODUCTION

The double-lobed radio galaxy 3C 390.3 (VII Zw 838) is classified as an *N*-type galaxy with $z = 0.057$ (Burbidge & Burbidge 1971; Penston & Penston 1973). The apparent magnitude of the galaxy is 15.38 ($B - V = 0.68$, $U - B = -0.69$) in the V band (Osterbrock 1977; Sandage 1967) and its absolute magnitude is -22.3 ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, and an optical spectral index α equal to 0.7). A strong optical emission line spectrum of this galaxy was first reported by Sandage (1967). Lynds (1968) and Burbidge & Burbidge (1971) detected a "double structure" in the Hβ line. The optical spectrum of this galaxy displays strong forbidden and weaker narrow emission lines, with very broad permitted lines (Osterbrock *et al.* 1976; Perez & Penston 1986).

A very strong "blue bump" begining at about 4000 Å was detected in 1971 (when this galaxy was in a high state) which gradually decreased and completely disappeared in 1980 when the optical continuum was relatively weaker (Shafer *et al.* 1985). Strong and variable optical continuum emission on a timescale of days to years was also observed in 3C 390.3 (Shen *et al.* 1972; Lloyd 1984).

Systematic radio observations were also made for this galaxy at different frequencies (Medd *et al.* 1972; Dent & Kapitzky 1976). It is a classical double-lobed radio source with "hot spots" at the leading edges of the structure and a compact central component (Hargrave & McEllin 1975). *IUE* observations of this galaxy between 1978 and 1986 have displayed variable line and continuum emissions (Clavel & Wamsteker 1987, and references therein).

Prior to the *EXOSAT*, x-ray observations of 3C 390.3 were carried out with Uhuru (Forman *et al.* 1978; Giocconi *et al.* 1972), Copernicus (Charles *et al.* 1975), Ariel V (Barr *et al.* 1980), *HEAO-1* (Marshall *et al.* 1978), and *Einstein* (Urry *et al.* 1989) x-ray telescopes which have shown flux variability and a soft excess in it. Results of the x-ray spectral analysis (power law fits) of 3C 390.3 have shown a different spectral index values, e.g., $1.65^{+0.50}_{-0.25}$ obtained from *HEAO-1* (Mushotzky 1984) and 2.18 obtained from *Einstein* IPC (Urry *et al.* 1989). Therefore a detailed x-ray spectral analysis of this source may provide important results about this broad line radio galaxy (BLRG), 3C 390.3. Also this galaxy is one of the rare AGNs which has double peaked broad emission lines which provide the direct evidence for accretion disks around super massive black holes (Oke 1987; Perez *et al.* 1988).

3C 390.3 was observed with the *EXOSAT* on seven epochs between 1984 and 1986. Out of seven spectra only one spectrum, which was noisy, has been published by Shafer *et al.* (1985). We searched the *EXOSAT* archives and found three spectra which were obtained between 1985 and 1986 with long exposures (very good signal-to-noise ratio spectra). In this paper we present the results of our analysis of these spectra of 3C 390.3. The spectrum of this galaxy displays a soft excess below 2 keV and the indication of an iron line at 6.4 keV. In Sec. 2 we present the observational details and the spectral analysis, and results are presented in Sec. 3. Finally we discuss the implications of the results in Sec. 4.

2. OBSERVATIONS

3C 390.3 was observed with *EXOSAT* on seven epochs between 1984 and 1986 using low energy telescopes (LE) and medium energy proportional counters (ME). Details of the *EXOSAT* instrumentation have been described by White & Peacock (1988), de Korte *et al.* (1981), and Turner *et al.* (1981) have described the details of the LE and ME detectors, respectively. Table 1 shows the log of LE and ME observations, and count rates of this source. The LE data were obtained with the Lexan 3000 (LX3), Aluminium/Parylene (Al/P) and Boron (B) filters. Background subtracted LE count rates with errors were obtained from the *EXOSAT* database and they were converted into the LE pulse height (PH) spectra using the x-ray analysis and data utilization (XANADU) software package. ME data were obtained from

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TABLE 1. Log of observation of the LE and ME spectra and count rates of 3C 390.3.

Start time			End time			LE count rate			ME count rate[a]
						LX3	Al/P	B	$(10^{-3}\ \mathrm{cm^{-2}\ s^{-1}})$ [a]
D	H	M	D	H	M	$(10^{-4}\ \mathrm{cm^{-2}\ s^{-1}})$			
1985/033	06	39	1985/033	09	14		1.51 ± 0.17	0.46 ± 0.07	2.48 ± 0.07
1985/033	09	31	1985/033	22	09	1.84 ± 0.34	1.51 ± 0.17	0.46 ± 0.07	2.60 ± 0.06
1986/076[b]	12	00	1986/076	22	59	2.30 ± 0.23	1.44 ± 0.17	0.73 ± 0.18	1.84 ± 0.04

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

eight argon filled proportional counters (each counter will be referred to as a "detector") which were divided into two parallel rows of four detectors (half 1 and half 2). These two halves can be either aligned to the pointing axis or offset by up to 2° to monitor the background. Background subtraction of the ME spectra were carried out using "swap" technique (Smith 1984; White & Peacock 1988; Yaqoob 1989) which removes the effect of the correlated background variability between the two halves of the ME experiment. The background spectra obtained from the offset detectors are different from the corresponding background spectra of the same detectors when they are aligned. Therefore, these background spectra were corrected using "difference spectra" and the corrected background spectra were subtracted from the on-source spectra to obtain the source spectra only. Also, background variability studies were carried out and were corrected following the method described by Morini *et al.* (1987). The above-mentioned background subtraction analysis of the three ME spectra of 3C 390.3 which are presented in this paper, were carried out at the *EXOSAT* Observatory Data Center, Noordwijk, The Netherlands.

3. ANALYSIS AND RESULTS

The x-ray spectral fitting (XSPEC) software package was used for the analysis of the LE and ME spectra of 3C 390.3 and all the spectra were analyzed separately to avoid systematic effects due to background variations and possible source variations. In the first instance, the simple power law model with uniform absorption in the line of sight to the source was used to fit the three datasets. The absorption cross sections given by Morrison & McCammon (1983) were used in the model. The best fit parameters of the power law model are presented in Table 2(a) along with the 90% confidence error bars which were computed for each parameter keeping all the other parameters free. The 90% confidence limits on each parameter were calculated by the procedure detailed by Avni (1976) and Lampton *et al.* (1976) ($\chi^2_{\mathrm{min}} + 4.61$ for two free parameters). We find from the χ^2_{red} statistics which are given in Table 2(a), that this simple power law model provides acceptable fits to all the datasets. However the values of the equivalent hydrogen column (N_{H}) along the line of sight of 3C 390.3 are smaller than the galactic column

TABLE 2. Spectral fits to the spectra of 3C 390.3.

(a) Power law + absorption

Date	Γ^{a}	N^{b}	N_{H}^{c}	Flux[d]		L_{x}^{e}		χ^2_{red}/dof
				0.1–2 (keV)	2–10 (keV)	0.1–2 (keV)	2–10 (keV)	
1985/033	$1.42^{+0.14}_{-0.14}$	$4.39^{+0.94}_{-0.79}$	$1.04^{+0.88}_{-0.57}$	1.25 ± 0.20	2.78 ± 0.08	1.75 ± 0.28	3.89 ± 0.11	1.18/26
1985/033	$1.60^{+0.11}_{-0.12}$	$6.08^{+0.96}_{-0.84}$	$2.34^{+1.23}_{-0.89}$	1.18 ± 0.22	2.90 ± 0.07	1.65 ± 0.31	4.06 ± 0.10	0.71/26
1986/076	$1.53^{+0.10}_{-0.09}$	$4.09^{+0.53}_{-0.48}$	$1.13^{+0.60}_{-0.42}$	1.60 ± 0.16	2.15 ± 0.05	2.24 ± 0.22	3.01 ± 0.07	1.04/29

(b) Power law + fixed absorption[†]

Date	Γ^{a}	N^{b}	χ^2_{red}/dof
1985/033	$1.56^{+0.08}_{-0.08}$	$5.36^{+0.60}_{-0.60}$	1.28/27
1985/033	$1.59^{+0.07}_{-0.07}$	$6.03^{+0.54}_{-0.53}$	0.78/27
1986/076	$1.73^{+0.06}_{-0.06}$	$5.30^{+0.4}_{-0.4}$	1.58/30

(c) Broken power law* + fixed absorption[†]

Date	Γ_1^{a}	Γ_2^{a}	N^{b}	χ^2_{red}/dof
1985/033	$2.59^{+0.64}_{-0.84}$	$1.43^{+0.14}_{-0.14}$	$2.48^{+2.26}_{-1.09}$	1.18/26
1986/076	$2.98^{+0.38}_{-0.42}$	$1.56^{+0.08}_{-0.09}$	$2.03^{+0.88}_{-0.59}$	1.04/29

*Break energy fixed at 0.6 keV.
[†] Fixed at the galactic N_{H} value ($4.1 \times 10^{20}\ \mathrm{cm^{-2}}$).
[a] Photon index.
[b] Normalization in 10^{-3} photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ at 1 keV.
[c] Column density in $10^{20}\ \mathrm{cm^{-2}}$.
[d] Flux in 10^{-11} ergs $\mathrm{cm^{-2}\ s^{-1}}$.
[e] Luminosity in 10^{44} ergs $\mathrm{s^{-1}}$.

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density value (0.41×10^{21} cm^{-2}) (Stark *et al.* 1991). These results imply that probably there is no significant absorption in this source. Next we fit the datasets using the above model but fixing the $N_{\rm H}$ value with the galactic $N_{\rm H}$ value and the results of the best fit parameters with 90% confidence error limits are presented in Table 2(b).

In Figs. 1(a) and 1(b) we show the observed LE and ME spectra of 3C 390.3 with the best fit model convolved through the detector response. Also the residuals between the spectra and the model are shown in the lower panels of the figures. There is marginal evidence of soft emission below 2 keV which can be seen from Figs. 1(a) and 1(b). It is evident from Table 1 that 3C 390.3 displayed weak flux variation, around 25%, on the timescale of a year. But we do not find any variation in the spectral index, $\alpha = (\Gamma - 1)$, between 1985 and 1986 and a mean value of α is 0.63 ± 0.07 which is in close agreement with the value obtained from *HEAO-1* ($\alpha = 0.65^{+0.50}_{-0.25}$, see Mushotzky 1984) but slightly less than the canonical value ($\alpha = 0.7$).

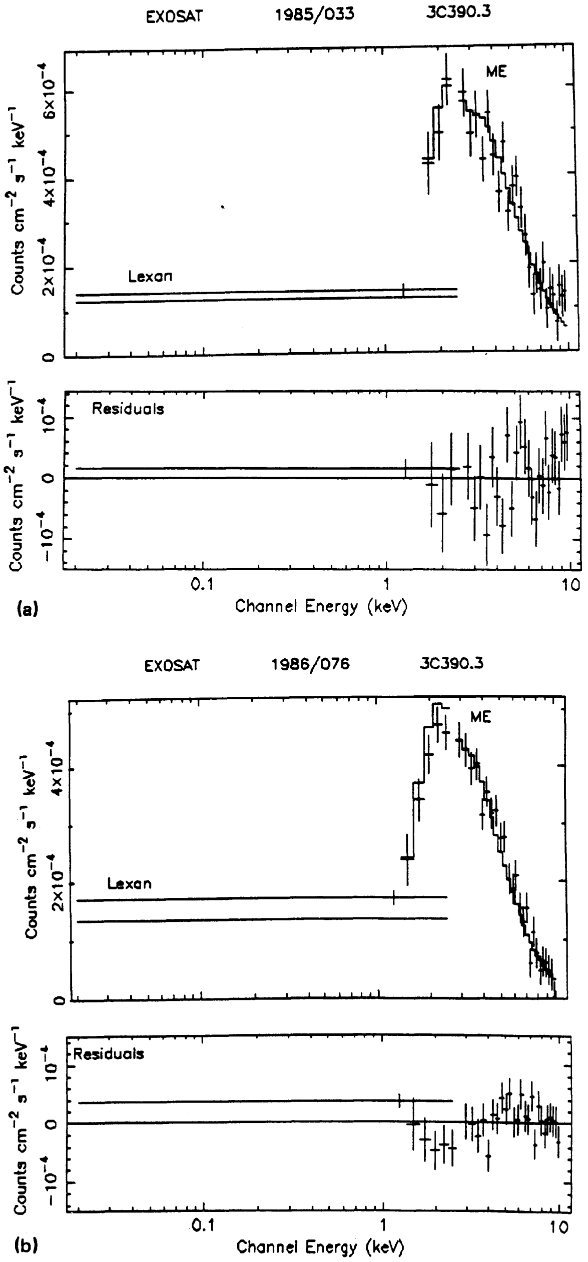

FIG. 1. Observed LE and ME spectrum of 3C 390.3 for (a) 1985/033 and (b) 1986/076 fitted with a simple power law and absorption model (fixed with the galactic $N_{\rm H}$ value). Lower panels of each figure show the residuals in units of counts cm^{-2} s^{-1} keV^{-1}.

Two power law and fixed absorption model provides better fits to the LE + ME datasets compared to that obtained from the single power law model. However the model became insensitive to change the fit parameters. But the broken power law model with the absorption fixed with the galactic $N_{\rm H}$ value and the break energy fixed at 0.6 keV (following Wilkes *et al.* 1989) fits well (the value of $\chi^2_{\rm red}$ is much smaller than the value obtained from the single power law model) with the datasets and the best fit parameters with 90% confidence error bars are listed in Table 2(c). Spectral index of the soft x-ray component is much steeper than the harder component.

Evidence for the presence of iron-K shell emission and absorption in the x-ray spectra of Seyfert galaxies is gradually increasing (Nandra *et al.* 1989; Leighly *et al.* 1989; Piro *et al.* 1990; Pounds *et al.* 1989, and references therein). Also the residuals presented in the lower panels of Figs. 1(a) and 1(b) show the presence of an emission feature around 6.0 keV.

Therefore, a Gaussian line feature with a fixed width of 0.1 keV and a variable line center was added with the power law and absorption model and were fitted with all the datasets. The best fit parameters with 90% confidence error bars are presented in Table 3. From the $\chi^2_{\rm red}$ statistics, we find that there are definite improvements in the fit with the addition of the Gaussian line around 6.0 keV. From the *F*-statistics we find that the inclusion of the Gaussian line is highly significant ($>99.9\%$). In Figs. 2(a) and 2(b) we show the spectra, shown earlier, along with best fit power law, absorption, and Gaussian line model convolved through the detector response. Also the residuals between the model and the observed spectrum are shown in the lower panels. From the best fit parameters we find that the line energies (see Table 3) are consistent with 6.05 keV, the value expected from fluorescence from a cold medium and the redshift of 3C 390.3 ($z = 0.057$). The best fit equivalent widths of the iron line with 90% confidence error bars are presented in Table 3. To compute the uncertainties in the equivalent width measurements, only statistical errors have been taken into account. We also fit the LE + ME spectra using a power law, blackbody model with a fixed absorber, but there were no improvements in the reduced chi square values compared to those obtained from the simple power law model. Also we used a thermal bremsstrahlung model to fit the data. However, the reduced chi square values are worse ($\chi^2_{\rm red} > 2.0$) than those obtained from the simple power law model and the plasma temperatures were very high.

4. DISCUSSION

The soft (0.1–2 keV) and hard (2–10 keV) x-ray luminosities of 3C 390.3 as measured with *EXOSAT* on three epochs, between 1985 and 1986, are listed in Table 2(a). From this table it can be seen that the hard x-ray source has undergone a weak change ($\sim25\%$) in a year's time. From the compari-

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TABLE 3. Power law + fixed absorption† + Gaussian line.

Date	Γ^a	N^b	E_L^c	E_N^d	EW^e	$\chi^2_{\rm red}$/dof
1985/033	$1.62^{+0.09}_{-0.09}$	$5.52^{+0.58}_{-0.60}$	$5.35^{+0.42}_{-0.40}$	$1.27^{+0.92}_{-0.91}$	343^{+248}_{-245}	1.10/25
1985/033	$1.61^{+0.07}_{-0.07}$	$6.11^{+0.55}_{-0.54}$	$6.83^{+1.57}_{-1.60}$	$0.64^{+1.07}_{-0.64}$	227^{+379}_{-227}	0.64/25
1986/076	$1.79^{+0.07}_{-0.06}$	$5.47^{+0.4}_{-0.4}$	$5.23^{+0.93}_{-0.39}$	$1.02^{+0.53}_{-0.52}$	369^{+192}_{-188}	1.25/28

† Fixed at the galactic $N_{\rm H}$ value (4.1×10^{20} cm^{-2}).

[a] Photon index.

[b] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV.

[c] Line energy in keV.

[d] Line intensity in 10^{-4} photons cm^{-2} s^{-1}.

[e] Equivalent width in eV.

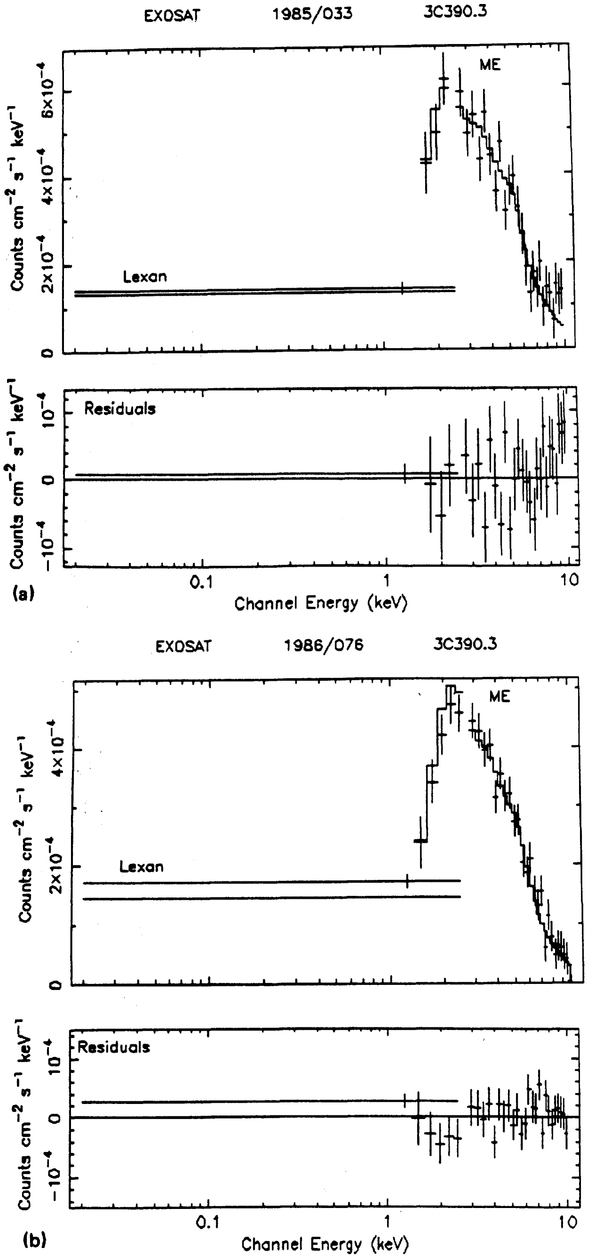

FIG. 2. Same as Fig. 1, but fitted with a power law, fixed absorption, and Gaussian line model.

sion of luminosities of this source as measured with *HEAO-1* (2.5×10^{44} ergs s^{-1}; Mushotzky 1984) and that obtained from *EXOSAT*, we find an increase in the luminosity of 3C 390.3 by a factor of 1.6 between 1978 and 1985. This source is known to display such variability on a longer timescale (Barr *et al.* 1980) but very short period x-ray variability (on timescales of hours, days, and weeks) is not known for this galaxy.

Significant soft excess was detected in 3C 390.3 from *Einstein* IPC + MPC data (Urry *et al.* 1989). *EXOSAT* results also show the presence of soft excess in this galaxy. A blackbody model ($T_{\rm BB}\sim250$ eV) provided good fit to the soft excess detected from IPC + MPC data but this model does not fit well with the *EXOSAT* LE + ME data. Also the thermal bremsstrahlung model is not acceptable to fit the LE + ME data. However, the broken power law model is preferred over the two power law or the thermal bremsstrahlung or the blackbody models. These results indicate that the steeper power law component at low energies is preferable than the other competing components of different models, to account for the soft excess of 3C 390.3.

Results of *IRAS* observations have revealed that 3C 390.3 shows a peak of emission at 25 μm (Edelson & Malkan 1987). Miley *et al.* (1984) have suggested that the peak emission at 25 μm is probably due to the dust. However, prior to the *IRAS* observations, Rees *et al.* (1982) predicted the appearance of this type of peak emission feature in the nonthermal spectra of radio galaxies. They proposed an ion-supported torus model in which synchrotron self-absorption frequency is ~30 μm (Rees *et al.* 1982; Begelman 1985, 1988). Perez et al. (1988) and Halpern & Chen (1989) have also suggested a relativistic accretion disk model for 3C 390.3 in which a quasi-spherical, hot ion torus occupies the inner disk and illuminates the thin outer disk. Therefore we suggest that the fluorescent iron line detected in the x-ray spectrum of 3C 390.3 [mean line center energy is 5.80 keV which is very close to the redshifted fluorescent line at 6.4 keV. Since the thermal bremsstrahlung model did not provide good fits to the x-ray spectra, the possibility of a thermal origin of helium-like iron line (6.7 keV) is very poor], is produced in the optically thick accretion disk where the nonthermal x-rays from the central source are reprocessed by absorption and scattering in the thick cold medium.

Finally we suggest that future long term multi-wavelength observations of this rare BLRG, which has also displayed type II Seyfert spectra with steepening of the broad line Balmer decrement as the continuum decreases (possibly due to the reddening of the BLR), would be extremely desirable to improve our understanding about the structure and dynamics of AGNs.

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