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X-ray spectrum of NGC 3783: detection of soft excess and an emission line

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Abstract. Results of the X-ray (0.1–10 keV) spectral analysis of the Seyfert I galaxy, NGC 3783, which was observed with EXOSAT on three epochs between 1983 and 1985, are presented here. No low energy absorption, intrinsic to the source, was found in this galaxy and the spectral index of the power law fit did not vary during the EXOSAT observations. Soft excess was detected in this source which has displayed correlated variabilities with the soft spectral index (of the broken power law fits) and the low energy count rates (or fluxes) of the galaxy. Soft excess was maximum when the source was in brightest state in 1984. Also, strong flux (both soft and hard) variations of NGC 3783 have been found on the time scales of 6 months. For the first time, we report the presence of a highly significant emission line around 6.0 keV in the spectrum of this galaxy. Measured equivalent width of the line is best estimated to be $\sim 146 \pm 77$ eV which indicates that the origin of the line may be due to the fluorescence of the cold iron around the central continuum source.

Key words: active galactic nuclei: individual (NGC 3783) – galaxies: Seyfert – galaxies: X-ray – spectroscopy

1. Introduction

NGC 3783 is one of the nearest and brightest ($z = 0.009$, apparent magnitude in the V band is 13.43 with $B-V = 0.56$ and $U-B = -0.70$ and the absolute magnitude is -20.2 using $H_0 = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$; $q_0 = 0$ and an optical spectral index equal to 0.7) highly luminous ($L_{\rm IR} > 10^{44}\ \mathrm{erg\,s^{-1}}$; Ward et al. 1988) Seyfert I galaxy (Osmer et al. 1974). This galaxy has displayed both optical continuum and emission line variability (Penfold 1979; Menzies & Feast 1983; de Ruiter & Lub 1986) but no significant optical polarisation has been detected in it (Brindle et al. 1990). This weak radio source (Penston 1977) is the first X-ray Seyfert galaxy identified from the Ariel V sky survey (Cooke et al. 1976). Later, this galaxy was observed with Einstein (Holt et al. 1989; Urry et al. 1989; Kruper et al. 1990), HEAO-1 (Mushotzky 1984) and EXOSAT (Turner & Pounds 1989) satellites. Results of Ariel V, HEAO-1 and EXOSAT observations show that NGC 3783 is a flat spectrum source and possible soft excess was detected in this galaxy from Einstein observations (Urry et al. 1989 and references therein).

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This galaxy was observed on 3 epochs with EXOSAT and only one spectrum has been published by Turner & Pounds (1989) using simple power law model. They could neither detect the soft excess nor the presence of iron emission line in this galaxy. In this paper we present the results of the detailed spectral (0.1–10 keV) analysis of NGC 3783 which was observed with EXOSAT by S.J. Bell-Burnell, between 1983 and 1985. Our results show that this galaxy has displayed both flux and soft excess variability during EXOSAT observations and a highly significant iron emission line (detected for the first time) is present in it. Also we find that the variability of the soft excess is correlated with the soft spectral index and the soft fluxes of the source. Implications of these results are discussed in Sect 4. Observations and the results of the spectral analysis are given in Sect. 2 and Sect. 3, respectively.

2. Observations

Lexan 3000 (LX3), aluminium/parylene (Al/P) and boron (B) filters were used with the low energy (LE) detectors (de Korte et al. 1981) to obtain the spectrum of NGC 3783 in the 0.1–2 keV range. Background subtracted LE count rates with errors (for this galaxy) were obtained from the EXOSAT database and using the XANADU (X-ray Analysis and Data Utilisation) software package, those count rates were converted into LE puluse height (PHA) spectra.

Spectra of this galaxy in the 2–10 keV range were obtained using the medium energy (ME) detectors (eight argon filled proportional counters) (Turner et al. 1981). Eight detectors were divided into two halves (detectors 1 to 4 are collectively known as half 1 and detectors 5 to 8 are collectively known as half 2) which can be either aligned to the pointing axis or offset by up to 2° to obtain background emissions. "Swap" technique (Smith 1984; White & Peacock 1988; Yaqoob; Warwick & Pounds 1989) was adopted for background subtraction of the ME spectra. Background subtraction analysis of the three ME spectra of NGC 3783 were carried out at the EXOSAT Observatory. Table 1 presents the log of LE and ME observations with the corresponding count rates.

3. Spectral analysis and results

Simple power law with uniform absorption (using the absorption cross sections given by Morrison & McCammon 1983) model was used to fit the LE+ME spectra of NGC 3783 (using XSPEC

Table 1. Log of observation of the LE and ME spectra and count rates of NGC 3783

Start time			End time			LE count rate (10^{-4} cm^{-2} s^{-1})			ME count rate[a] (10^{-3} cm^{-2} s^{-1})
(d)	(h)	(min)	(d)	(h)	(min)	LX3	Al/P	B	
1983/347	10	44	347	18	42	2.53 ± 0.33			4.24 ± 0.06
1984/162	17	08	162	23	00	10.61 ± 0.77	6.37 ± 0.42	1.68 ± 0.20	7.92 ± 0.07
1985/005	05	38	005	12	07	3.62 ± 0.32	2.68 ± 0.28	0.95 ± 0.16	5.16 ± 0.05

[a] The count rates are for PHA channels 6 to 35 correspoding to the energy range 2 to 10 keV with the best signal-to-noise ratio.

Table 2. Spectral fits to the spectra of NGC 3783
(a) Power law + absorption

Date	α[c]	N[d]	N_H[e]	χ_r^2/d.o.f.
1983/347	$0.32^{+0.07}_{-0.07}$	$6.50^{+0.67}_{-0.61}$	$6.41^{+4.00}_{-2.30}$	1.48/28
1984/162	$0.40^{+0.03}_{-0.04}$	$13.60^{+0.60}_{-0.70}$	$2.12^{+0.58}_{-0.45}$	1.08/32
1985/005	$0.40^{+0.05}_{-0.04}$	$8.95^{+0.58}_{-0.53}$	$6.93^{+2.35}_{-1.72}$	1.75/32

(b) Power law + fixed absorption[b]

Date	α[c]	N[d]	Flux[f]		L_X		χ_r^2/d.o.f.
			0.1–2 (keV)	2–10 (keV)	0.1–2 (keV)	2–10 (keV)	
1983/347	$0.35^{+0.06}_{-0.06}$	$6.79^{+0.58}_{-0.55}$	1.33 ± 0.17	4.81 ± 0.07	0.58 ± 0.07	2.10 ± 0.03	1.49/29
1984/162	0.50	15.70	3.04 ± 0.22	8.78 ± 0.08	1.32 ± 0.09	3.83 ± 0.03	3.59/33
1985/005	$0.43^{+0.03}_{-0.04}$	$9.34^{+0.46}_{-0.46}$	1.81 ± 0.16	5.83 ± 0.06	0.79 ± 0.07	2.54 ± 0.03	1.78/33

(c) *Two power law*[a] *+ fixed absorption*[b]

Date	α_1[c]	N_1[d]	α_2[c]	N_2[d]	χ_r^2/d.o.f.
1983/347	0.58	7.36	0.33	7.40	1.35/27
1984/162	4.94	0.47	0.42	14.20	0.97/31
1985/005	0.43	4.67	0.43	4.67	1.90/31

(d) Thermal bremsstrahlung + fixed absorption[b]

Date	kT[k]	N[d]	χ_r^2/d.o.f.
1983/347	$50.45^{+45.10}_{-17.98}$	$1.77^{+0.31}_{-0.31}$	1.69/29
1984/162	22.54	4.63	5.05/33
1985/005	$25.88^{+6.07}_{-4.32}$	$2.84^{+0.24}_{-0.25}$	1.80/33

(e) Broken power law[a] *+ fixed absorption*[b]

Date	α_1[c]	α_2[c]	N[d]	χ_r^2/d.o.f.
1983/347	$1.70^{+0.80}_{-0.80}$	$0.33^{+0.07}_{-0.06}$	$3.26^{+8.64}_{-1.54}$	1.49/28
1984/162	$4.09^{+0.28}_{-0.33}$	$0.42^{+0.04}_{-0.03}$	$2.18^{+0.51}_{-0.39}$	0.85/32
1985/005	$1.90^{+0.68}_{-0.98}$	$0.40^{+0.04}_{-0.04}$	$4.21^{+2.98}_{-1.37}$	1.68/32

software package). Results of the best-fit parameters along with 90% confidence errors which were computed following the procedure given by Lampton et al. 1976, are given in Table 2a. Derived values of the low energy absorption (N_H) are smaller than the galactic N_H value (9.4 10^{20} cm^{-2}; Stark et al. 1990). However the values of N_H obtained from Einstein IPC and HEAO-1 observations of NGC 3783 are $2.5^{+0.6}_{-0.8}$ 10^{21} cm^{-2} (Kruper et al. 1990) and 2.9 ± 1.6 10^{22} cm^{-2} (Mushotzky 1984), respectively. Table 2b shows the results of the best-fit parameters of the above model but the N_H value was fixed with the galactic value. In Fig. 1 we show the observed LE and ME spectra which was observed on 1983/347, along with the best-fit model (power law + fixed absorption) convolved through the detector response and the residuals between the spectra and the model are shown in the lower panel of this figure. Figure 2 presents the residuals of 1983/347, 1984/162 and 1985/005 which shows the presence of variable soft excess in this galaxy. Two power law, the thermal bremsstrahlung and broken power law models were used to fit the soft excess detected in this galaxy. Two power law model (Table 2c) provides acceptable fits to the data sets but the model is insensitive to compute the errors and there were no improvements in the reduced χ^2 (χ_r^2) values of the thermal bremsstrahlung model (Table 2d) than that obtained from the power law and fixed absorption model. Best-fit parameters of the broken power law model (break energy fixed at 0.6 keV following Wilkes et al. 1989) are presented in Table 2e which shows that this model provides good fit to the soft excess. Interestingly it can be noted that the soft spectral index (α_1) values are correlated with the soft excess values. However, the value of the hard spectral index (α_2) was constant during the EXOSAT observations.

Recently, EXOSAT and Ginga observations have revealed the presence of iron emission and absorption lines in the X-ray spectra of AGNs (Pounds 1989; Leighly et al. 1989; Pounds et al.

Table 2 (continued)

(*f*) *Power law + fixed absorption*[b] *+ Gaussian line*

Date	α^c	N^d	$E_L{}^h$	$E_N{}^i$	EW^j	χ_r^2/d.o.f.
1983/347	$0.42^{+0.07}_{-0.07}$	$7.22^{+0.67}_{-0.63}$	$5.32^{+0.25}_{-0.26}$	$1.55^{+0.78}_{-0.78}$	169+85	1.10/27
1985/005	$0.47^{+0.04}_{-0.05}$	$9.63^{+0.51}_{-0.49}$	$5.60^{+0.54}_{-0.72}$	$1.21^{+0.69}_{-0.69}$	124+70	0.60/31

[a] Break energy fixed at 0.6 keV; [b] Fixed at the galactic N_H value (9.4 10^{20} cm^{-2}); [c] Photon index; [d] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV; [e] Column density in 10^{20} cm^{-2}; [f] Flux in 10^{-11} erg cm^{-2} s^{-1}; [g] Luminosity in 10^{43} erg s^{-1}; [h] Line energy in keV; [i] Line intensity in 10^{-4} photons cm^{-2} s^{-1}; [j] Equivalent width in eV

1989). Also the residuals of the spectra of NGC 3783 presented in Fig. 2, show the presence of an emission feature around 6 keV. A Gaussian line component with variable line center energy was added with the power law and fixed absorption model and was used to fit the LE + ME spectra. Best fit parameters with 90% confidence errors are presented in Table 2f. From the comparison of the χ_r^2 values presented in Tables 2b and 2e, it is seen that there were positive improvements in the χ^2 statistics and also the *F*-statistic show that the inclusion of the Gaussian line is highly significant (>99.9%). The line center energy and the equivalent width of the line is best estimated to be $5.5^{+0.4}_{-0.5}$ keV and 146 ±77 eV (mean value obtained from the two data sets), respectively. To compute the errors of the equivalent widths, only the statistical errors have been considered. In Fig. 3 the observed LE + ME spectra with the best fit model (power law + fixed absorption + Gaussian line) convolved through the detector response are shown and the residuals between the spectra and the model are presneted in the lower panel of this figure.

4. Discussion

HEAO-1 observations have already shown that the flux of NGC 3783 varied on 6 months time scale (Mushotzky 1984). Results of the EXOSAT observations also displayed strong variability of the LE and ME fluxes of this galaxy on the time scales of 6 months (Table 2b). However, from the comparison of the results obtained from Einstein (Kruper et al. 1990 and references therein), HEAO-1 (Mushotzky 1984) and EXOSAT (Table 2b) observations, we

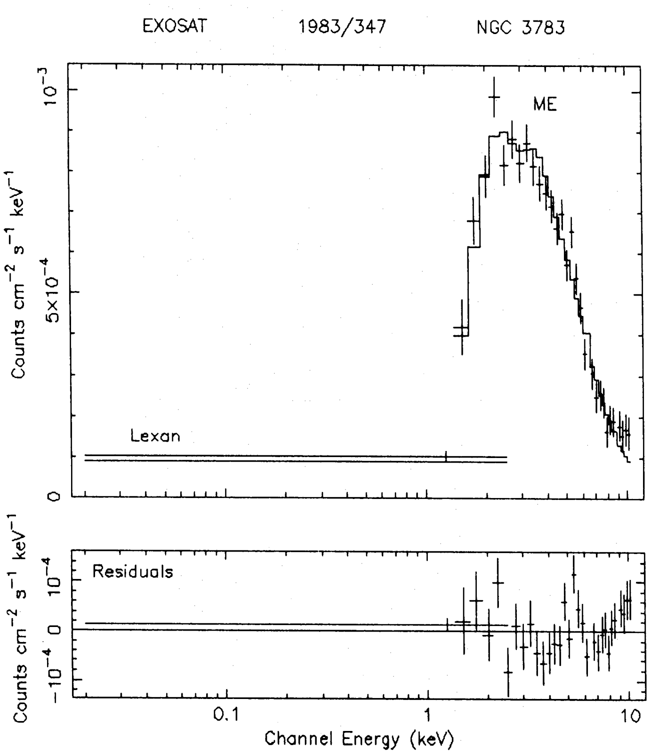

Fig. 1. Observed LE and ME spectra of NGC 3783 along with the best-fit model (power law + fixed absorption) convolved through the detector response. Residuals between the spectrum and the model are shown in the lower panel

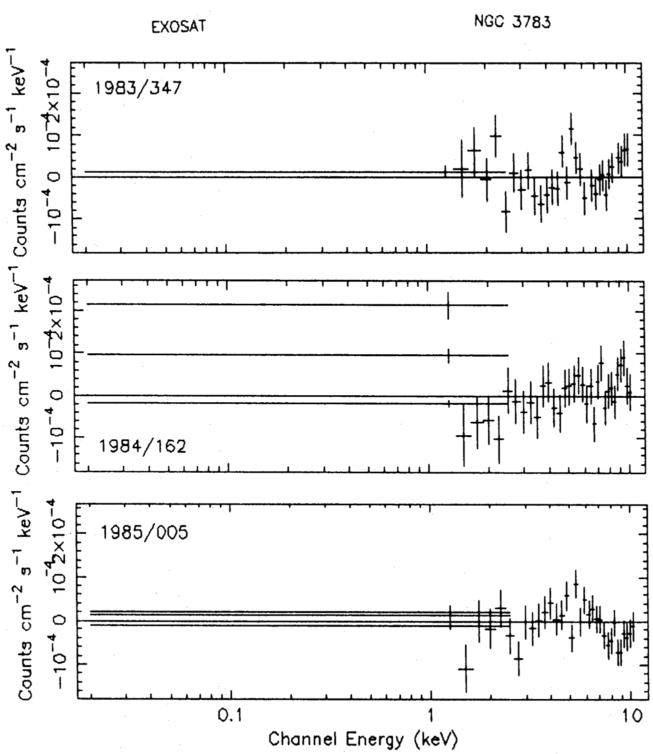

Fig. 2. Residuals between the model (powerlaw + fixed absorption) and the spectra (LE + ME) of NGC 3783 which were observed on three epochs. This figure clearly shows the presence of variable soft excess in this galaxy

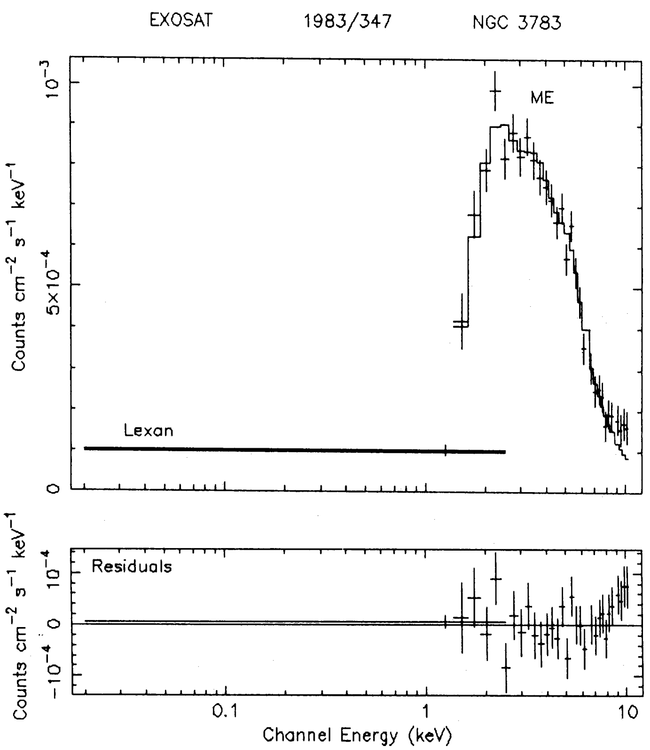

Fig. 3. Observed spectrum (LE+ME) of NGC 3783 fitted with the power law + fixed absorption + Gaussian line model convolved through the detector response. Residuals are shown in the lower panel of this figure

do not find any dramatic long-term variations of the X-ray fluxes (or luminosities) of this source.

Simple power law fits (Table 2b) show that there were no variations of the spectral index ($\alpha = 0.43 \pm 0.05$) during EXOSAT observations. However, the results of the broken power law fits (Table 2e) suggest that the hard spectral index (α_2) of this galaxy was also, practically, unchanged, between 1983 and 1985 but the soft spectral index (α_1), below 0.6 keV, varied during the above period. Possible soft excess was detected in NGC 3783 from Einstein IPC + MPC data but the EXOSAT results have shown that this galaxy displayed strong soft excess in its spectrum. The variability of the soft excess is correlated with α_1 and the LE count rates or fluxes of the source (relatively much weaker correlation is also present between the soft excess and the ME count rates or fluxes). This galaxy was in brightest state when the soft excess and the LE and ME count rates were maximum. Also, during the brightest state of NGC 3783, the relative increase of the LE flux was larger ($\sim 130\%$) than that of the ME flux ($\sim 80\%$). The physical cause of such relative variations of the X-ray fluxes is not known. However, here we will present one speculated scenario. X-ray flux or luminosity variations of a galaxy depends on the variations of the central continuum source which can vary if the accretion rate varies. Again the variability of the accretion rate depends on many parameters and one such important parameter is the distribution of matter, around the central compact object, to be accreted. Thus the high accretion rate of a galaxy can lead it to the brighter state. In general, during the brighter state of a galaxy, both the soft and hard X-ray fluxes will increase as has been observed in NGC 3783. If part of the hard X-rays get reprocessed and emit soft X-rays, then the source will become softer and the soft excess can be seen in the spectrum of the galaxy. The present scenario which is a purely speculative one, can explain the observed results of NGC 3783. However, one should not take it literally. The measured line center energy ($5.5^{+0.4}_{-0.5}$ keV) of the detected emission line is consistent neither with the redshifted fluorescent iron line at 6.4 keV nor with the helium-like iron line at 6.7 keV. However, the measured value of the line center energy is closer, considering the uncertainities, to the redshifted 6.4 keV iron line and the reason for the observed inconsistency of the line energy may be due to the poor spectral resolution of the ME detector which is about 1.2 keV FWHM at 6.0 keV. Also the measured equivalent width (146 ± 77 eV) of the emission line suggest that the origin of the line may be due to fluorescence of the cold iron (Inoue 1989). If the origin of the line is due to the helium-like iron line which arises from the hot ($\sim 10^8$ K) thin plasma, then the equivalent width of the line will be much larger (Inoue 1989) than the measured value for this galaxy. Thus we suggest that the detected emission line (around 6.0 keV) in the X-ray spectra of NGC 3783 is, most probably, due to the fluorescence of the cold iron around the central continuum source but outside of our line-of-sight (since no low energy absorption has been detected in NGC 3783).

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