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The ultraviolet to X-ray spectrum of the Seyfert 1 galaxy E 1615+061: accretion disk and reflection models

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Abstract. The Seyfert 1 galaxy E 1615+061 is a candidate for the strongest variability in soft X-rays, changing from a very steep high state ($\Gamma \simeq 4$), as implied by HEAO1 observations performed in 1977, to a two orders of magnitude dimmer state with a flatter spectrum ($\Gamma \simeq 2$), as observed by EXOSAT in 1985. In this paper we present the results of a campaign of (quasi)-simultaneous observations with IUE, ROSAT and GINGA in 1990-1992. We found that the X-ray luminosity was about 6 times larger than observed by EXOSAT, though the object did not attain the level observed by HEAO-1. The UV to X-ray spectrum observed in our campaign shows the presence of a UV bump and a soft X-ray excess. These components are formally fitted by a standard thin accretion disk model. We find however that this model is not self-consistent, due to the high level of ionization expected for the high value of accretion rate, which leads to an over-production of soft X-rays by reflection. A self-consistent explanation is found in the low accretion rate regime. In this case reflection by mildly ionized regions of the disk produces the soft excess and the direct emission from the disk accounts for the UV emission but does not extend to the soft X-ray region. Some evidence for a line at around 0.6 keV, attributed to OVII/OVIII, supports the presence of an ionized reflector. The spectra observed by EXOSAT and HEAO1 can be successfully explained by this model in the regimes of very low and high accretion rates.

Key words: galaxies: individual: E 1615+061 – galaxies: nuclei – galaxies: Seyfert – ultraviolet: galaxies – X-rays: galaxies

1. Introduction

The presence of a soft X-ray excess has been established in a large fraction of Seyfert galaxies (e.g. Turner & Pounds 1989, Walter & Fink 1993). The limitation in bandwidth and resolution of the instruments and the presence of several components in the X-ray spectrum make however its origin still unclear. A good determination of the shape of the intrinsic power law, which should take into account the presence of a reflection hump at high energies (e.g. Piro, Yamauchi & Matsuoka 1990, Pounds et al. 1990) and the low energy absorption edges produced by warm absorber (e.g. Nandra et al. 1993) is particularly important for measuring the soft X-ray excess (e.g. Piro, Matt & Ricci 1995; Pounds et al. 1994)

In one common scenario, the soft X-ray excess is considered to be the high energy tail of a broad–band component which dominates the emission in the optical–UV range (UV bump) and that is produced by thermal emission of an accretion disk. (e.g. Czerny & Elvis 1987).

An alternative explanation of the soft X-ray excess is suggested by the presence of reprocessing of hard X-ray photons first indicated by GINGA. Detailed studies of reprocessing in ionized disks (Ross & Fabian 1993, Matt, Fabian & Ross 1993, Zycki et al. 1994), aimed primarily at accounting for the presence of strong iron lines in some Seyfert galaxies (e.g. Piro, Matsuoka & Yamauchi 1992), have shown that soft X-rays can be reflected (by Thomson scattering) by ionized regions of the disk. In this case the soft X-ray excess would be the low energy equivalent of the high energy bump (Czerny and Zycki 1995).

The Seyfert 1 galaxy E 1615+061 (Pravdo et al. 1981) is an object well suited to explore these problems and test the models. Previous observations have shown a very high spectral variability associated with large variations of the luminosity below 1 keV (Piro et al. 1988). Piro et al. argued that such a behaviour could have been produced by a variable soft excess that, at the highest levels of intensity, shifts to higher energies, dominating the hard component even above 1 keV. At the lowest levels it shifts to very low energies, leaving visible the bare intrinsic power law also below 1 keV.

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Table 1. Observation log

Date	Satellite/Instr.	Duration (min.)
Mar. 13, 1990	GINGA/LAC	150
Aug. 11, 1990	IUE/SWP (#39443)	420
Aug. 11, 1990	IUE/LWP (#18564)	70
Aug. 11-13, 1990	ROSAT/PSPC	10
Feb. 19-20, 1991	ROSAT/PSPC	190
Mar. 3 1992	IUE/SWP (#44105)	395

The purpose of organizing a multiwavelength campaign on this object, that comprises IUE, ROSAT and GINGA observations was thus aimed to:

- measure the broad band X-ray spectrum of the object;
- verify whether the UV to soft X-ray emission can be interpreted as a single spectral component, according to accretion disk models;
- attempt to measure the variations of the soft X-ray excess and its correlation with luminosity and test whether disk models are able to account for the observed spectral dynamics.

The paper is organized as follows. The results of the observations obtained by IUE, ROSAT and GINGA along with a reanalysis of the EXOSAT data are presented in Sect. 2. In Sect. 3 we discuss in more detail the soft X-ray excess. In Sect. 4 we discuss the disk models of the UV and soft X-ray components. We summarize and discuss the results in Sect. 5.

The distance adopted for the luminosity is 228 Mpc, corresponding to $z = 0.038$ (Pravdo et al. 1981) and $H_0 = 50$ km s^{-1} Mpc^{-1}.

2. Observations and data analysis

EXOSAT observations were performed in 1985 (Piro et al. 1988). The spectrum has been reanalyzed. The log of the new observations of E 1615+061 is presented in Table 1. A first set of observations was performed in 1990 under the RIASS program, that allowed a simultaneous observation with ROSAT and IUE. A GINGA observation was performed a few months before this. Other observations with ROSAT and IUE were performed in 1991 and 1992. In the following all the best fit parameter errors, unless otherwise specified, are computed for $\Delta\chi^2 = 2.7$, corresponding to the 90% confidence level for one parameter of interest.

2.1. IUE

Prior to ours, an IUE observation performed on January 2, 1982 (SWP #15925, T=63 min, LWR #12260 T= 40 min) gave null results, probably due to a mispointing in the blind offset procedure reported in the log book.

Our observations were treated using standard IUE processing. The resulting spectra are shown in Fig. 1. They are typical

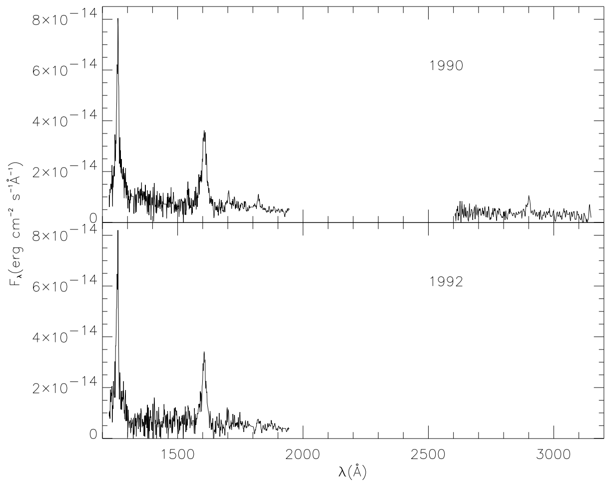

Fig. 1. IUE spectra of E 1615+061 obtained in 1990 and 1992

of a Seyfert 1 galaxy, showing several emission lines, in particular strong and broad Lyα and CIV.

The continuum was measured in wavelength bins where the contribution of lines should be negligible (e.g. Maraschi et al. 1991). Those regions are listed in Table 2 along with the flux and the associated error that includes a 10% systematic error to account for calibrations uncertainties (Hackney, Hackney and Kondo 1984) and residual contamination of lines in continuum bins. The continuum points were fitted with a power law ($f_\lambda = \lambda^{-\alpha_\lambda}$) modified by reddening according to Seaton (1979), with $E(B-V) = 0.1$, corresponding to the galactic column density $N_{HG} = 4.2\ 10^{20}$cm^{-2} (Stark et al. 1992) as per Bohlin, Savage & Drake (1978). The power law fit gives $F^c_{1500} = (1.5 \pm 0.15)\ 10^{-14}$erg cm^{-2} s^{-1}Å^{-1}, $\alpha_\lambda = 1.66 \pm 0.19$ for the combined SW and LW spectra taken in 1990 and $F^c_{1500} = (1.3 \pm 0.13)\ 10^{-14}$erg cm^{-2}s^{-1}Å^{-1}, $\alpha_\lambda = 1.35 \pm 0.50$ for the SW spectrum taken in 1992. F^c_{1500} is the flux at 1500 Å corrected for reddening. No significant difference is present between the two observations, and the 1990 data set will be used in Sect. 4 in conjunction with X-ray data.

Both spectra taken in 1990 and 1992 show the presence of strong broad Lyα and CIV lines. In the LW exposure of 1990 the MgII line is also present (Fig. 1). The intensity of Lyα and CIV lines, estimated after subtraction of the best fit power law, are presented in Table 3. The associated errors result from adding in quadrature a 10 % uncertainty on the continuum level and a 5 % calibration uncertainty. Line intensities are constant. The ratio Lyα/CIV$\simeq$ 1.6 is typical of Seyfert galaxies (e.g Netzer 1990).

2.2. GINGA

E 1615+061 was observed with the Large Area proportional Counters (LAC) aboard GINGA for a full day. Background data were obtained by pointing at a region near the target for one day. Background subtraction was performed as described in Matsuoka et al. (1990). The source was significantly detected

Table 2. UV continuum fluxes

λ(Å)	F(1990) $(10^{-15}\mathrm{erg\ cm^{-2}s^{-1}Å^{-1}})$	F(1992)
1352	10.2 ± 1.1	6.8 ± 0.8
1400	7.9 ± 1.0	6.8 ± 0.9
1500	6.6 ± 0.8	6.4 ± 0.8
1755	6.2 ± 0.7	5.6 ± 0.6
1875	4.8 ± 0.5	4.6 ± 0.5
2625	3.7 ± 0.6	
2675	3.7 ± 0.5	
2725	3.7 ± 0.4	
2775	3.4 ± 0.4	
2975	3.1 ± 0.4	
3025	2.9 ± 0.4	
3095	2.3 ± 0.4	

Note: the bandwidth of each point is 50 Å, except for the point at 1352 Å, where the bin is 45 Å. Errors include 10% systematic errors

Table 3. UV line intensities

	$I(10^{-12}\mathrm{erg\ cm^{-2}s^{-1}})$	EW (Å)
Lyα(1990)	1.17 ± 0.09	136^{+31}_{-26}
Lyα(1992)	1.10 ± 0.08	152^{+33}_{-27}
CIV(1990)	0.74 ± 0.07	110^{+24}_{-21}
CIV(1992)	0.59 ± 0.06	98^{+24}_{-20}

with a count rate of 4.2 cts/s in the range 1.7-18 keV. Spectra were accumulated for every orbit and then summed separately for remote and contact orbits. Since no difference was found between these spectra, we summed all data together, for a total effective integration time of 9120 s.

A simple power law model provides a good fit to the spectrum in the range 1.7-27 keV, with a spectral index of 1.8 and no evidence for significant absorption. The fit results in Table 4 are obtained after fixing N_H at the galactic value. A search for an iron line in the range 6.4-6.8 keV gives a negative result. However the upper limit of 1 keV for the EW is not significant compared with the typical value of 150 eV observed in Seyfert galaxies.

More relevant to the issue of the soft excess is the effect of a Compton reflection hump on the slope of the power law. We therefore fitted the GINGA spectrum with a model consisting of an intrinsic power law plus a reflection hump, described by

$$F(E) = C\ E^{-\Gamma}(1 + rA(E,\Gamma)) \cdot\ exp(-\sigma N_H) \qquad (1)$$

where $A(E,\Gamma)$ is the albedo described using the prescriptions of Lightman and White (1988). An upper limit $r < 1.8$ is obtained for the relative intensity of the reflection component, a value consistent with that expected for a face-on disk ($r \simeq 1.3$). The best fit spectral index is $\Gamma = 1.8^{+0.14}_{-0.08}$, where the upper value $\Gamma = 1.94$ corresponds to the maximum in the reflection component. Similar results are obtained by fitting the reflection model of Matt, Perola & Piro (1991) that includes the iron line emission.

2.3. ROSAT

E 1615+061 was observed with the ROSAT-PSPC (Trümper 1983, Pfefferman et al. 1986) twice, the first time during the All Sky Survey under the RIASS program, the second time during the AO-1 phase. The RIASS data were analyzed as in Walter and Fink (1993), using an extraction radius of 5 arcmin for the source and an annulus between 7 and 30 arcmin (after eliminating a faint serendipitous source, see Sect. 2.5) for the background. For the pointed observation we used an extraction radius of 3 arcmin for the source, and an annulus between 3.5 and 5.5 arcmin for the background. The large cell for source extraction was adopted to ensure that all low energy counts were included, given the electronic ghost imaging that widens the point spread function below 0.3 keV (Hasinger et al. 1992). Spectra were binned with a minimum S/N ratio in each bin of 4 and 10 for survey and pointed observations respectively. We performed spectral fits using the March 1992 matrix, appropriate for observations performed before Oct. 1991 (Fiore et al. 1994; ROSAT News n.27), but excluding from the analysis the first 7 ($<$ 0.08 keV) and last 16 channels ($>$ 2.4 keV), where the response matrix is poorly determined. A systematic error of 2% was added in quadrature to the statistical errors to account for residual calibration uncertainties.

The spectra of the two observations were fitted with a simple power law. Best fit parameters are presented in Table 4. The spectra are consistent with each other, both in slope and, within 10%, in normalization. Comparison with the GINGA results shows that the spectrum in the ROSAT range is steeper ($\Delta\alpha \simeq 0.4$, when $N_H = N_{HG} = 4.2\ 10^{20}\mathrm{cm}^{-2}$), even when we consider the maximum value of Γ allowed by GINGA with the reflection model and compare it with the spectral index derived in the fit to the ROSAT AO-1 observation with N_H unconstrained.

2.4. EXOSAT

The observation presented in Piro et al. (1988), which include data from the ME detector and the LE telescope with Lexan 3000 and Al/P filters, was reanalyzed to take into account the updated value of the galactic column density from Stark et al. (1992) given in Sect. 2.3. Results of the spectral fitting with a simple power law are presented in Table 4.

2.5. Serendipitous sources near E 1615+061

Images of the Einstein IPC, EXOSAT LE and ROSAT PSPC AO-1 fields centered on E 1615+061 have been studied by Massaro, Nesci & Piro (1994) and by Nesci et al. (1996) to look for alternative candidates for the event observed by HEAO-1. They conclude that E 1615+061 remains the most likely source of the high flux observed in that instance.

Table 4. Summary of X-ray data of E 1615+061

Satellite	C$^{(1)}$	Γ	$N_H^{(2)}$	χ^2_ν	$F_S^{(3,4)}$	$F_H^{(3,5)}$
EXOSAT	0.3 ± 0.1	1.6 ± 0.4	$0.5^{+2.2}_{-0.5}$	1.0	1.0	1.6
”	0.7 ± 0.15	2.2 ± 0.3	4.2 fix	1.14		
GINGA	2.5 ± 0.3	1.79 ± 0.08	4.2 fix	0.99		8.9
ROSAT ASS	2.7 ± 0.3	2.1 ± 0.5	3.3 ± 1.4	0.86	6.0	
”	2.7 ± 0.3	2.4 ± 0.2	4.2 fix	0.86		
ROSAT AO1	2.4 ± 0.07	2.1 ± 0.1	3.4 ± 0.3	1.0	6.0	
”	2.5 ± 0.06	2.34 ± 0.05	4.2 fix	1.3		

Note: $^{(1)}$ 10^{-3}cm^{-2}s^{-1}keV^{-1} $^{(2)}$ 10^{20}cm^{-2} $^{(3)}$ 10^{-12}erg cm^{-2} s^{-1} $^{(4)}F(0.1-1$ keV) $^{(5)}F(2-10$ keV)

In this section we will estimate the possible contamination of those serendipitous sources to the EXOSAT-ME and GINGA-LAC spectra presented in this paper. Only two sources, considering their position and count rate - greater than about 1/10 of that of E 1615+061 in the PSPC observation (0.53 ± 0.007), could contaminate the spectra of the high energy instruments.

The first is a star located 14 arc min off E 1615+061 with a net count rate of 0.051 ± 0.003 cts/s. The extrapolation of the spectrum (Nesci et al. 1996) to the ME and LAC ranges is negligible compared to the measured spectrum, as already pointed out in Piro et al. (1988) for the ME.

The other source is located in the outer ring of the PSPC image ($\sim$ 35 arc min off-axis), outside the field of view of the EXOSAT LE and Einstein IPC and the HEAO-1 error box. Its position corresponds with the radio galaxy 4C6.55. The net PSPC count rate is 0.31 ± 0.01 cts/s. Taking into account collimator responses, the extrapolation of its spectrum (Nesci et al. 1996) gives a maximum contribution of 8% and 17% to the LAC and ME count rates respectively. Since those values are lower than the typical statistical errors of the two spectra, we conclude that the results are not significantly affected by contamination of this source.

3. The soft X-ray excess

3.1. The evidence

The spectral steepening observed in the ROSAT range does not necessarily imply an intrinsic soft excess. In the case of a warm absorber, the presence of an ionized edge around 0.7 keV (e.g. Nandra et al. 1993) would result, at energies below the edge, in an excess above the extrapolation of the power law flattened by the effect of the photoelectric absorption in the range 0.7- 2 keV. It is therefore important to fit jointly the ROSAT data with the higher energy data available from GINGA, where the spectral continuum shape is dominated by the intrinsic power law.

The ROSAT all sky survey observation was the nearest to the GINGA observation. The fluxes in the overlapping region around 2 keV are consistent and there is no significant evidence of variation. In fact a fit with a simple power law with α and N_H free is satisfactory (χ^2_ν = 1.1) and gives a spectral index similar to that derived from the fit on GINGA data alone. Absence of negative residuals in the range 0.6-0.9 keV excludes an edge from a warm absorber.

The value of column density derived from the fit, N_H = 2.3 ± 0.4 $10^{20} cm^{-2}$, is significantly lower than the galactic column density, even after taking into account the typical error of ± 1.0 10^{20} (90% confidence level) on this determination (Elvis et al. 1986). This indicates the presence of a soft excess in the lower part of the ROSAT range, basically below 0.6 keV. We have therefore fitted the spectrum with a two component model, a power law and a soft component described by a thermal bremsstrahlung, with N_H fixed at the galactic value (hereafter we will keep N_H fixed at this value). The fit is good (χ^2_ν = 0.92) and is shown in Fig. 2a. The temperature of the soft excess, $kT = 0.2 \pm 0.1$, and the flux of the soft component in the 0.1-1 keV range, equal to 60 % of the flux of the power law, are similar to the values observed in other Seyfert galaxies (Walter et al. 1994). Power law parameters are identical with the fit to GINGA data alone.

The GINGA and ROSAT AO1 spectra show a small ($\simeq$ 10%) mismatch in the levels of the two normalizations that may introduce artefacts in a combined fit. We prefer to fit the ROSAT AO1 data alone adopting for the slope of the intrinsic power law two choices, Γ = 1.8 and Γ = 2.0, where the higher value was chosen to represent the case of the maximum contribution of the reflection component allowed by GINGA data. The results of the fits with a power law and a soft component described either with a thermal bremsstrahlung or a black body model are presented in Table 5. They are consistent with, but better constrained than those derived using the combined GINGA - ROSAT All Sky Survey data. In Fig. 2b we show the best fit spectrum obtained for the thermal bremsstrahlung model and a power law with Γ = 1.8 (Fig. 2b).

3.2. The variability

E 1615+061 increased its luminosity by a factor of 6 from the EXOSAT observations in 1985 to the GINGA observation in 1990 (Table 4). The following ROSAT All Sky Survey (Aug. 1990) and ROSAT AO1 (Feb. 1991) were consistent with each other and with the GINGA luminosity within 10%.

How did the soft component change with a factor of six variation observed in hard X-rays ? We attempted to estimate its behaviour by fitting the EXOSAT data with the same models adopted in the previous section for ROSAT. The results are presented in Table 5. In the case of EXOSAT the temperature of the excess is very low and in the Table 5 we give the 90 % upper limit on its value.

From Table 5 we note that the luminosity of the soft component increases with that of the hard one. The relative flux of the soft component goes from 20^{+60}_{-16}% to 53 ± 7% at high luminosities. This spectral softening is however not significant. Also marginal is the increase of the temperature with luminosity.

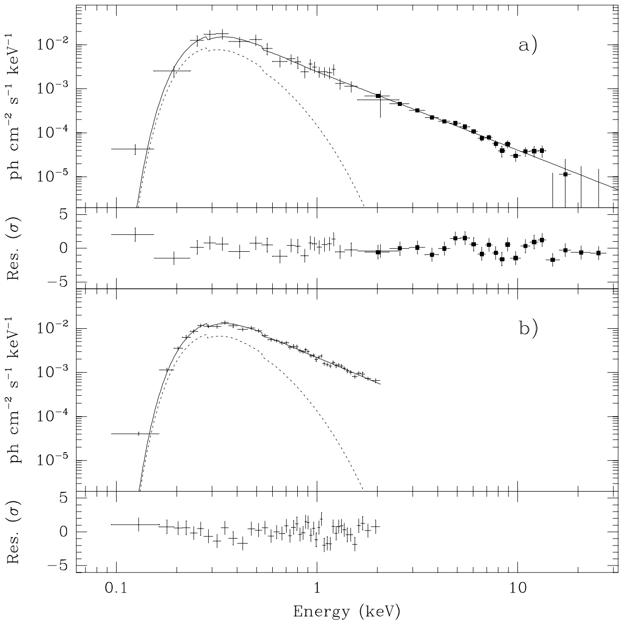

Fig. 2a and b. A fit with a power law and thermal bremsstrahlung model (the latter shown separately with a dotted line) to the combined ROSAT all sky survey and GINGA spectra (**a**) and to the ROSAT pointed observation (**b**)

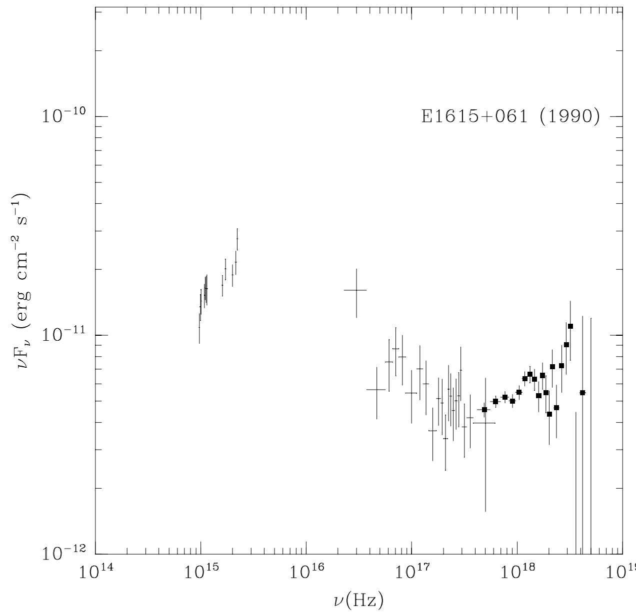

Fig. 3. IUE continuum, ROSAT and GINGA spectra of E 1615+061 in 1990 corrected for Galactic absorption

Table 5. Soft excess parameters for EXOSAT and ROSAT AO-1 observations

Satellite	Γ	$kT(eV)$	F^1_{excess}	$F^1_{p.l.}$	χ^2_ν
p.law+bl.body					
EXOSAT	1.8	< 70	$0.1^{+0.3}_{-0.08}$	0.5	1.0
ROSAT	1.8	77 ± 6	1.5 ± 0.1	2.8	1.31
EXOSAT	2.0	< 60	$0.1^{+0.2}_{-0.08}$	0.66	1.0
ROSAT	2.0	70 ± 15	0.9 ± 0.3	3.4	1.15
p.law+th.brems.					
EXOSAT	1.8	< 160	$0.1^{+0.3}_{-0.08}$	0.5	1.0
ROSAT	1.8	220 ± 30	1.6 ± 0.1	2.8	1.07
EXOSAT	2.0	< 150	$0.05^{+0.25}_{-0.04}$	0.66	1.0
ROSAT	2.0	180 ± 50	0.9 ± 0.3	3.3	1.06

Note: (^{1}) Flux in the 0.1-1 keV for the excess and power law in 10^{-12}erg cm^{-2}s^{-1}

4. Origin of the UV and soft X-ray components: accretion disk and modifications due to reprocessing

In Fig. 3 we present the spectrum, corrected for absorption, of E 1615+061 obtained in 1990 with the simultaneous observations of IUE, ROSAT and the quasi simultaneous observation of GINGA. The spectrum is presented in a νF_ν plot where X-ray data points are, as usual, normalized to the best fit model, in this case the thermal bremsstrahlung model for ROSAT data, convoluted through the instrumental response matrix.

The bulk of the luminosity is located in the EUV- soft X-ray range. We now attempt to explain self-consistently the overall UV to soft X-ray spectrum. In the first instance we examine the case of thermal radiation from a thin accretion disk. We then study the modification of the soft-X-ray spectrum produced by reflection from the inner regions of the disk ionized by X-rays from the central source.

4.1. *Thin accretion disk*

For the thin accretion disk spectrum we adopt the prescriptions of Czerny and Elvis (1987) corrected for the bound - free opacity after Maraschi and Molendi (1990). A preliminary analysis performed without these corrections gave essentially the same results, but for a slightly higher value of the accretion rate (Balucinska-Church et al. 1994). We have additionally included a power law component from UV to X-rays, distinguishing the two cases Γ = 2 and Γ = 1.8. Innermost radius of the disk is 3 Schwarzschild radii, corresponding to a conversion efficiency of 6%. We assume that the accretion disk is face-on (Kirhakos and Steiner 1990), and the viscosity parameter is 0.1. Best fit parameters (Table 6) have been obtained by fitting the model to the data from the 1990 IUE observation and the 1991 ROSAT observation. With Γ = 1.8 the fit is unsatisfactory (χ^2_ν = 2.2), while it becomes marginally acceptable with Γ = 2 (Fig. 4a). There are some residuals around $\nu = 1.4 \cdot 10^{17}$ Hz (E=0.6 keV) whose origin will be addressed in Sect. 4.3. In any case, with the large value of $\dot{m}$ (the accretion rate in Eddington units) implied by this fit, it is likely (Ross & Fabian 1993) that the disk is ionized by the hard X-rays and is reflective at low energies, thus modifying the spectrum in soft X-rays. In the next section we shall verify that this could actually be the case.

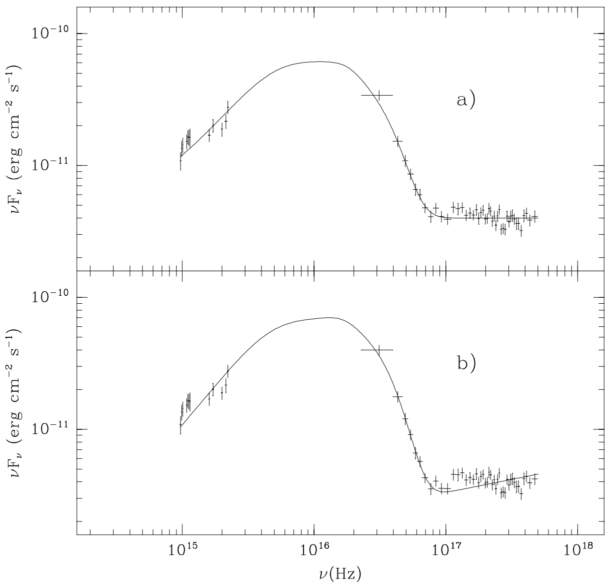

Fig. 4. a Fit of the accretion disk model to the IUE and ROSAT AO1 data. The underlying power law spectral index is fixed at Γ = 2. **b** Same as **a** in the case Γ = 1.8

Table 6. Thin accretion disk model: results

	Γ = 1.8	Γ = 2
M	$(5.4 \pm 0.3)10^6 M_\odot$	$(5.0 \pm 0.3)10^6 M_\odot$
$\dot{m}$	(0.95 ± 0.03)	(0.85 ± 0.03)
χ^2_ν	2.2	1.3

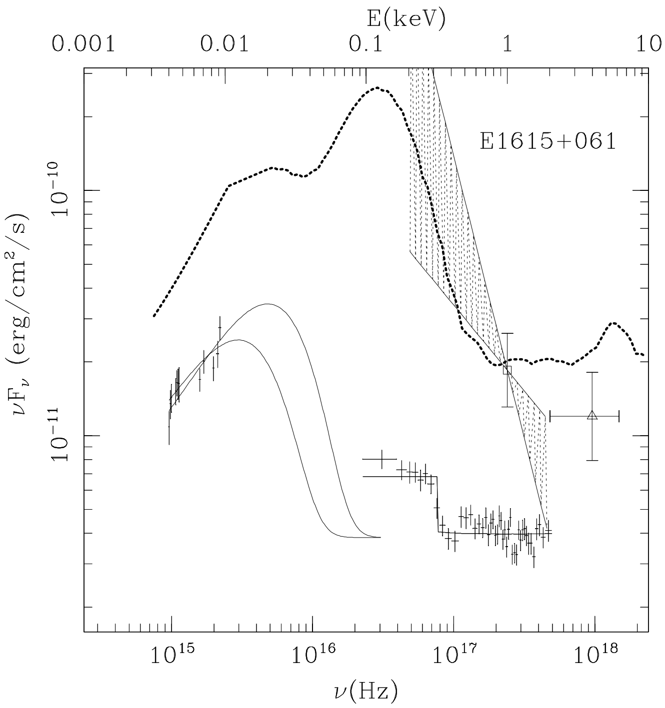

Fig. 5. Fit of the mildly ionized accretion disk model (continuous lines) to the IUE and ROSAT data (crosses). The UV spectrum is produced by direct emission from the accretion disk. The left curve corresponds to the values ($\dot{m}_{min}$ = 0.033, M_{max} = 38 · 10^6 $M_\odot$), the right one to ($\dot{m}_{max}$ = 0.1, M_{min} = 18 · 10^6 $M_\odot$, see text). The soft X-ray excess is produced by reflection by a mildly ionized disk, which reflects X-rays below 0.3-0.4 keV. In the case M_{min} = 18 · 10^6 $M_\odot$, increasing the accretion rate to $\dot{m}$ = 0.5 (thick dotted line), brings the disk in a highly ionized state, that well reproduces the spectrum observed in the high state by HEAO1 LED (shaded area from 0.2 to 2 keV) and A2 (triangle).

4.2. Reprocessing effects on the soft X-ray spectrum

Detailed studies of reprocessing in ionized disks (Ross & Fabian 1993, Matt, Fabian & Ross 1993; Zycki et al. 1994), have given relevant results on the issue of the soft X-ray excess. The inner regions of the disk can be photo-ionized by X-rays emitted from the central source. If the ionization level is such that the light elements, like He, C, O, - the main contributors to photoelectric absorption at low energies - are fully (or nearly) stripped of electrons, the medium becomes "reflective" by Thomson scattering to X-rays. In this instance the soft X-ray excess would be the low energy equivalent of the high energy bump (Czerny and Zycki 1995).

The key quantity in determining the ionization state of the disk is the ionization parameter, $\xi = \frac{L_0}{nR^2}$, where L_0 is the luminosity of the ionizing source and n the density of the disk. The radial law of the ionization parameter depends on the geometry of the X-ray source. We have adopted an optically thick spherical X-ray source of radius equal to R_0 . The conclusions we derive remain however basically unchanged in the case of a point source above the disk at height R_0 .

When we express L_0 as $f\eta\dot{M}c^2$, that is a fraction of the accretion luminosity, and use the density n of a thin accretion disk around a Schwarzschild black hole (Shakura and Sunyaev 1973), we obtain

$$\xi(r) = 1.8 \cdot 10^9\ \dot{m}^3\ f\alpha\eta^{-2}r_0^{-7/2}\left[1-\left(\frac{6}{r}\right)^{1/2}\right]^2 \cdot G(r/r_0) \quad (2)$$

where $r_0 = R_0/R_G$, $R_G = GM/c^2$, and

$$G(r/r_0) = \left(\sin^{-1}\frac{r_0}{r} - \frac{r_0}{r}\left[1-(\frac{r_0}{r})^2\right]^{1/2}\right)\cdot\left(\frac{r_0}{r}\right)^{3/2} \quad (3)$$

is a factor taking into account the source geometry.

For $10 < r_0 < 40$, Eq. (2) can be approximated at $r = r_0$ to give (with η = 0.06, α = 0.1)

$$\xi(r_0) \simeq 500f\left(\frac{\dot{m}}{0.1}\right)^3\ \left(\frac{r_0}{20}\right)^{-5/2} \quad (4)$$

To estimate the ionization state of the disk model determined in the previous section, we make use of two constraints. First, for self-consistency we require that the primary source of optical - UV photons is accretion rather than reprocessing of hard X-ray photons (e.g. Perola & Piro 1994). As shown by Perola & Piro (1994) in Eqs. (6) - (9) this is verified at every radius when

$$r_0 < 20/f, \quad (5)$$

which, by Eq. (4) implies that

$$\xi(r_0) > 500 \left(\frac{\dot{m}}{0.1}\right)^3 f^{7/2} \quad (6)$$

Second, the ionizing luminosity is estimated by integrating the power law with Γ = 2 from 13.6 eV up to 30 keV, the limit of the GINGA spectrum. This gives $L_0 = 1.9 \cdot 10^{44}$erg s^{-1}, which corresponds, for the best fit values of the mass and accretion rate given in Table 6, to f = 0.35. From Eq. (6) we therefore have $\xi(r_0) \simeq 5000$. For this value of the ionization parameter the disk would be highly ionized and reflective to soft X-rays (e.g. Ross & Fabian 1993, Matt, Fabian & Ross 1993), thus leading to further enhancement of the soft X-ray excess. Hence the thin accretion disk model without reflection, discussed in Sect. 4.1, appears to be not self-consistent from this point of view.

4.3. A self-consistent accretion disk model with the O-UV produced by accretion and the soft X-ray excess by reflection

The result obtained in the previous section indicates that a possible explanation for the combined UV-soft X-ray spectrum could be sought in the low accretion rate regime, that is when the direct emission from the accretion disk does not extend to include the soft X-ray excess. The latter should be then produced through reflection by ionized regions of the disk. The UV spectrum can be fitted by the thin accretion disk model with the parameters ($\dot{m}, M$) comprised between ($\dot{m}_{min}$ = 0.033, M_{max} = $38 \cdot 10^6\ M_\odot$) and ($\dot{m}_{max}$ = 0.1, M_{min} = $18 \cdot 10^6\ M_\odot$).

For $\dot{m}$ = 0.033 the spectrum cuts off just above the last UV point, thus minimizing the disk luminosity. The upper limit of $\dot{m}$ corresponds to a spectrum extending into the EUV, without affecting significantly the soft X-ray range (Fig. 5). In the latter case f = 0.8 and, substituting in Eqs. (5) and (6) we get respectively $r_0 < 25$ and $\xi(r_0) > 230$. A value $\xi(r_0) \simeq 200$ can be attained also at lower accretion rates, provided that $r_0 \simeq 10$. Adopting this value of $\xi(r_0)$ and taking into account the radial dependence of the ionization parameter (Eq. (2)) we have that $30 < \xi(r) < 230$ in the region of the disk between r_0 and 1.5 r_0. Being very near to the central source, this region intercepts about 40% of the X-ray photons illuminating the whole disk. For ξ = 60 the oxygen is mostly in the He-like ionization state whereas He and H and C are fully ionized. We have adopted this value as representative of the average ionization state of the inner part of the accretion disk and have computed the corresponding X-ray albedo adopting the prescription of Lightman and White (1988) and the cross section given in Krolik and Kallman (1984).

We have then fitted the ROSAT PSPC AO1 spectrum with a reflection model (Eq. 1) with Γ = 2 and N_H equal to the galactic value. The best fit spectrum is shown in Fig. 5. The value of χ^2_ν, equal to 1.26, is not fully satisfactory. This is mostly due to positive residuals in the range 0.5 - 0.8 keV, which indicates the presence of a line. The simple reflection model adopted here describes, in fact, only the continuum. Detailed models of the reflected component produced by a disk, that include line emission, have been computed by Ross and Fabian (1993) and Matt, Fabian & Ross (1994) for the highly ionized case. Zycki et al. (1994) also covered in their treatment the mildly ionized case, the one that applies to our situation. Typical lines include OVIII (E=0.65 keV) and OVII (E=0.57 keV), with an EW that depends on the ionization parameter. For the range of ionization parameters expected in our case, Zycki et al. predict OVII/OVIII lines with EW$\simeq 20 - 50$ eV. Furthermore evidence for line emission at around 0.6 keV has been presented in the case of the Seyfert 1 galaxy NGC 3783 (George, Turner & Netzer 1995). In the case of E 1615+061, the addition of a line gives a satisfactory fit (χ^2_ν = 1.05) with a 99.5% confidence level improvement in χ^2 (Bevington 1969). Best fit values of energy E_L = (0.66 $\pm$ 0.1) keV and I_L = (3.2 $\pm$ 1.8) 10^{-4}cm^{-2}s^{-1}, corresponding to an EW= (54 $\pm$ 30 eV), are obtained.

The relative normalization of the reflected component (r = 0.7 $\pm$ 0.1) is proportional to the solid angle subtended by the ionized part of the disk at the central source. The ratio of r derived from the soft excess and of the upper limit on r on the high energy bump indicates that at least 40% of the photons illuminating the whole disk are reflected by the ionized regions of it, in agreement with the value derived previously from $\xi(r)$.

4.4. Origin of the soft X-ray emission observed in the high state

In the observation performed by the Low Energy Detectors onboard HEAO1 in 1977 (Pravdo et al. 1981), the source showed a very steep spectrum, described by a power law with Γ = 3.5 $\pm$ 0.8. The flux observed below 1 keV at that time was greater than observed by EXOSAT and ROSAT by a factor of about 100 and 10 times respectively. Comparing the relatively flat spectrum ($\Gamma \simeq 2$) observed by EXOSAT with that of HEAO1, Piro et al. (1988) tentatively suggested that such a spectral variation could have been produced by a comparatively small change in the temperature of a thermal component describing the soft excess. In the high state the soft component shifts to higher energies, dominating the emission up to about 1 keV.

A similar explanation has been proposed for the unusually steep spectra observed in Narrow Line Seyfert 1 Galaxies by Pounds, Done & Osborne (1995). They propose that the strong soft X-ray emission observed in these objects is due to disk accretion at nearly the Eddington limit, in analogy with the soft spectra observed in the high state of Galactic black hole candidate systems, like Cyg X-1.

We can therefore attempt to explain the high state emission observed in E 1615+061 by increasing the value of $\dot{m}$ in the disk models discussed above. The model in Sect. 4.1 can be immediately rejected, because the $\dot{m}$ required to explain the "mid" state was already close to the Eddington limit.

The model in Sect. 4.3 looks more promising in this respect. For values of $\dot{m}$ greater than about 0.2, the effects of ionization become substantial in determining the soft X-ray spectrum. In addition to the reflection effect, the thermal emission from the disk is enhanced by the bremsstrahlung contribution from hot electrons produced by ionization (Ross & Fabian 1993). A detailed disk model that includes all these effects has been computed by Matt, Fabian & Ross (1993). The geometry they adopt is that of a point source lying above the disk at a distance of 20 R_G, a size similar to that derived for the spherical central source in the previous section. Differences due to the different radial law of the ionization parameter are negligible for our purpose. The luminosity of the central source is equal to the accretion luminosity (f = 1). This assumption is consistent with the result of the previous section, where a similar value of f has been derived to describe the spectrum observed by ROSAT and IUE.

We have adopted the value Γ = 2, assuming that the intrinsic power law does not change significantly its slope in the high state. We will comment on this assumption in the following. We have produced a grid of model spectra for different values of $\dot{m}$ and for the range of masses derived in Sect. 4.3. We have compared these spectra with the information available on the spectrum in the high state, as presented in Pravdo et al. (1981). This is summarized in Fig. 5, where the HEAO1-LED measurements are represented by the shaded region, corresponding to the upper and lower limits on the spectral slope, centered on the point at 1 keV. The 2-6 keV data point represents the HEAO1-A2 simultaneous measurement.

The dotted line represents the model which best reproduces the observation, and corresponds to the case $M = 18 \cdot 10^6 M_\odot$, $\dot{m}$ = 0.5. Note that, while the spectrum in the range 0.2-1 keV has basically the same slope as observed, at higher energies it is dominated by the combined contribution of the intrinsic component and its reflected part. In this range the predicted spectrum is above - yet consistent with - the measurement. A better agreement could be achieved with some degree of anisotropy which would reduce the level of the direct component. Another possibility is that in the high state the slope of the intrinsic power law gets steeper. This is suggested by the similarity with the spectrum of NLS1 galaxies, which show a soft X-ray emission similar to that observed in E 1615+061 in the high state: in one of the two cases in which spectral measurements above 2 keV are available, the intrinsic power law is steep, with a slope $\Gamma \simeq 2.6$ (Pounds, Done & Osborne 1995). A verification of these alternatives should wait for more precise measurements of the spectrum of E 1615+061 in another high state.

If an increase by a factor of five in the accretion rate can reproduce successfully the transition from the IUE-ROSAT mid state to the HEAO1 high state, a decrease of a similar factor can also explain the very low state observed by EXOSAT, when the flux was 6 times lower than that of ROSAT. The accretion rate would be then so low that only H and He would be fully ionized, and the disk would reflect only photons with $E < 0.05$ keV.

Some predictions of the model can be tested by future observations. In the high state the reprocessed component should be characterized by features produced by the ionized disk, in particular an iron line at 6.7 keV (Fig. 5). We note also that the predicted amplitude of UV variations is lower than that observed in the X-ray range. The UV continuum level in the high state would be only two or three times greater than that observed by IUE in 1990. A decrement by a similar factor is expected in the low state. In this case the peak of the UV emission should shift below 2×10^{15} Hz and be detectable by UV measurements.

5. Discussion and conclusions

The results of our campaign of observations with GINGA and ROSAT have shown that E 1615+061 is indeed a highly variable source. The source was a factor of 6 brighter in the ROSAT and GINGA observations compared to the EXOSAT observation, although it did not reach the level observed by HEAO1 in 1977, remaining a factor of about 10 less. The huge soft X-ray variability implied by the HEAO1 observation of E 1615+061 (Pravdo et al. 1981, Piro et al. 1988) has been recently observed in other AGN (Boller et al. 1993; Otani et al. 1995; Brandt, Pounds & Fink 1995; Grupe et al. 1995; Boller et al. 1994; Dahlem, Heckman & Fabbiano 1995), mostly Narrow Line Seyfert 1 galaxies (NLS1, Boller, Brandt & Fink 1996). In the case of the two NLS1 Zwicky 159.034 (Brandt, Pounds & Fink 1995) and IRAS 13224-3809 (Otani et al. 1995) the overall spectral shape did not vary substantially with the luminosity, remaining extremely steep both in the low and the high state ($\Gamma \simeq 4$), whereas in the case of E 1615+061 the spectrum appears to be very steep only in the high state ($\Gamma \simeq 4$, Pravdo et al. 1981). On the contrary another NLS1, WPVS 007 (Grupe et al. 1995), shows spectral variations similar to that of E 1615+061.

As a matter of fact the overall spectrum of E 1615+61 observed by IUE, ROSAT and GINGA does not show any peculiarity that may be linked with the large variability. The UV spectrum (as well the optical, Nesci 1995, private communication) is characterized by the presence of typical broad emission lines, not consistent with those observed in NLS1.

The spectrum in the ROSAT range is significantly steeper than the GINGA spectrum. The joint ROSAT - GINGA spectrum indicates that the origin of the spectral steepening is produced by an excess component below 0.6 keV rather than by an absorption edge from a warm absorber.

We have tried to explain self-consistently the overall UV to soft X-ray spectrum in the framework of accretion disk models. We have thus fitted the combined UV-soft X-ray continuum with a thin accretion disk model after Czerny and Elvis (1987) including the upgrade in the bound- free opacity treatment proposed by Maraschi & Molendi(1990). The result is formally acceptable but when we take into account the effects of ionization by the central X-ray continuum we find that the model is not self-consistent. For the high value of the accretion rate required by the model ($\dot{m}$ = 0.85) the disk would be strongly ionized and thus would over-produce soft X-ray photons by reflection.

A self-consistent explanation is found in a low accretion rate regime. In this case reflection by mildly ionized regions of the disk ($\xi \simeq 100$) produces the soft X-ray excess, while direct emission from the disk accounts for the UV emission, without extending to affect the soft X-ray region. The UV spectrum can be fitted with $(\dot{m}, M)$ comprised between ($\dot{m}_{min}$ =

$0.033, M_{max} = 38 \cdot 10^6 \ M_\odot$) and ($\dot{m}_{max} = 0.1, M_{min} = 18 \cdot 10^6 \ M_\odot$).

We also find evidence of the presence of an emission line at 0.6 keV with an equivalent width of (53 ± 30) eV consistent with the OVII-OVIII line from an ionized disk (Ross & Fabian 1993, Zycki et al. 1994). Similar lines may have already been detected in other Seyfert galaxies observed by ROSAT (Turner et al. 1991) and by ASCA (George, Turner & Netzer 1995).

Finally, we compare the variations of the soft component with the predictions of this model, assuming that variations are driven by accretion rate. At low accretion rates (EXOSAT low state) the direct spectrum from the disk cuts off in the UV region. The disk is basically cold, only H and He would be fully ionized, producing a reflection component below about 0.05 keV. Increasing the accretion rate brings the disk to a mildly ionized state (ROSAT-GINGA). The tail of the UV emission remains below the soft X-ray range, but now the disk is ionized at a level such as to reflect X-rays below about 0.4 keV, and to produce an OVII line at around 0.6 keV. Finally for $\dot{m} \simeq 0.5$ the disk becomes highly ionized. The soft X-ray emission is then boosted by the combined effects of bremmstrahlung emission from hot electrons produced by the ionizing continuum, the reflected continuum itself and the direct emission from the accretion disk, that shifts into the soft X-ray band. This would explain the high state steep spectrum observed by HEAO1. In such a state we expect the presence of an iron line from a ionized reprocessor at around 6.7 keV.

Further observations with high sensitivities and better spectral resolution in the range where the X-ray reflection takes place are needed to verify the validity of the model proposed for the soft excess in the ROSAT data.

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