The nature of the X-ray source in NGC 4151

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Abstract

Analysis of broad-band X/γ-ray spectra of NGC 4151 from contemporaneous observations by *GRO*/OSSE, *ROSAT*, *Ginga* and *ASCA*, shows that the data are well modelled with an intrinsic spectrum due to thermal Comptonization. The X-ray spectral index changes from $\alpha \sim 0.4$ to 0.7, and temperature stays at about 50 keV. The X-ray spectrum varies in such a way that it is consistent with the roughly constant soft γ-rays, with pivots at $\sim$ 100 keV.

The UV/X-ray correlation observed by *EXOSAT* and *IUE* can be explained by two specific models with reprocessing of X-rays by cold matter. The first one is based on reemision of the X-ray flux absorbed by clouds in the line of sight. The model predicts no Compton reflection which is consistent with the broad-band spectra. The second model, assumes reprocessing of X-rays and γ-rays by a cold accretion disk with dissipative patchy corona. The homogenous corona model is ruled out here, since the hardness of the X-ray spectrum implies that the plasma is photon starved. The accretion disk model predicts Compton reflection which is only marginally allowed by the observations. Both our models satisfy the energy balance, and provide a good fit to the X/γ-rays and UV data.

Spectral Variability

• We analyze the brad-band spectra of NGC 4151 from contemporaneous observations by OSSE, *ROSAT* and *Ginga* in May-July 1991 (Fig. 1), and by OSSE and *ASCA* in May 1993 (Fig. 2). We find the high-energy data are well described by a thermal Comptonization model (Titarchuk & Mastichiadis 1994). The X-ray energy spectral index is $\sim$ 0.65 and 0.45, and the plasma temperature is $\sim$ 65 and 45 keV for the 1991 and 1993 observations, respectively. The spectra show no Compton reflection component. We also analyze other observations of NGC 4151 by OSSE, which shows that all the observed spectra and fluxes are very similar and can be described by thermal Comptonization at $kT \simeq 60$ keV.

Comparison of Figs. 1 and 2 shows that the pattern of spectral variability in NGC 4151 consist of varying X-ray power law pivoting at $\sim$ 100 keV. The spectrum breaks around that energy, thus permitting the γ-ray spectrum to stay approximately constant. This is consistent with the observations by OSSE.

• We also reanalyze X-ray observations from *IUE/EXOSAT* campaigns in 1983 November 7-19 and 1984 December 16-1985 January 2 (Perola et al. 1986). We have refitted the *EXOSAT* data with the thermal Comptonization spectrum at constant $kT = 60$ keV using a dual neutral absorption and a constant soft X-ray excess component. This results in close to linear correlation between the absorption-corrected EF_E at 5 keV (of the power law only) and at 8.5 eV from *IUE* de-reddened observations (Ulrich et al. 1991; Perola & Piro 1994). The values of EF_E in X-rays and UV are simillar, which may suggest the origin of the UV from some form of reprocessing of X-rays.

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The Transmission Model

• We assume that the UV flux is due to reemission of the X-ray flux absorbed by small, Thomson-thin clouds, which absorption is directly measured in X-rays, and the absorbing clouds are dense enough for almost complete termalization. We determine the temperature of the absorber as $kT \simeq 3$ eV by requiring that the spectral index in the UV between 8.5 and 7.2 eV equals the average observed value, α = -0.15 (Ulrich et al. 1991; Perola & Piro 1994).

• Fig. 3 compares results from the model with the data. The model predicts:

$$F_{UV} = f F_{abs} + F_0$$

where F_{UV} is the integrated UV flux, $F_0 = 0.05$ keV cm^{-2} s^{-1} is a residual UV flux, and the factor $f = 0.60$ takes into account a covering of the X-γ source by the clouds as well as an efficiency of the absorbed flux conversion into the blackbody continuum. The model does satisfy the energy balance, since $f < 1$ (i.e. there is more than enough power in the absorbed X-rays to account for the observed UV flux). The model predicts also no Compton reflection which is consistent with the broad-band spectra.

The typical column density of a cloud in the partial covering absorber is $N_H \simeq 10^{23}$ cm^{-2} with the typical covering factor of $\simeq 0.5$. The N_H of the complete absorber is a few time less. The size of a single cloud is $r_c \lesssim 10^7$, since the dominant thermalization process in 8.5 eV is free-free, and we require the free-free optical depth to be > 1. The average size of the entire absorber is $\sim 10^{14}$ cm, which satisfy the limit $r \lesssim 10^{15}$ cm from the relative UV/X-ray time delay (Warwick et al. 1995). The parameters of the absorber are consistent with those studied by Ferland & Rees (1988) and Guilbert & Rees (1988).

The Reflection Model

• We assume that the X-γ source forms a patchy, dissipative corona above the surface of an accretion disk. The homogenous corona is ruled out here, since the hardness of the X-ray spectrum implies that the plasma is photon starved. The optically-thick disk reprocesses a fraction of the X-γ flux into the UV radiation reemited locally as a blackbody. We assume that all dissipation takes place in the corona (Haardt & Maraschi 1993; Svensson & Zdziarski 1994). Contrary to the previous model by Perola & Piro (1994) with an optically thick central sphere irradiating a surrounding disk, our model does satisfy the energy balance with the cut off at $\sim$ 100 keV as seen by OSSE.

• We integrated the blackbody emission over the disk surface with the standard disk dissipation rate (Shakura & Sunyaev 1973). This realte the observed 8.5 eV flux to the total UV flux as a function of $r_S \mu^{1/2}$, where r_S is the Schwarzschild radius, and μ is a cosine of the disk inclination angle (we assume μ=0.42 from *HST* observations, Evans et al. 1993). The model predicts:

$$F_{UV} = 2(1 - A)\mu R F_{X\gamma}$$

where A is an albedo for the total X-γ flux, $F_{X\gamma}$, and R is a ratio of the corona emission intercepted by the disk to the luminosity emitted outward. Compton reflection for $R < 0.5$ is consistent with the broad-band spectra.

Fig. 4 compares predictions of the model with the data. We find that all $0 < r_S < 2.4 \times 10^{12}$ cm fit the UV spectral indices. This corresponds to the reflection limit of $\mu R \gtrsim 0.15$ (R $\ll 1$ would not be consistent with the assumption that reprocessing is in the disk). The value of r_S = 1.3×10^{12} cm provides the best fit (the solid line on fig. 4) to the absorbed fluxes inferred from the X-ray data for $\mu R = 0.21$.

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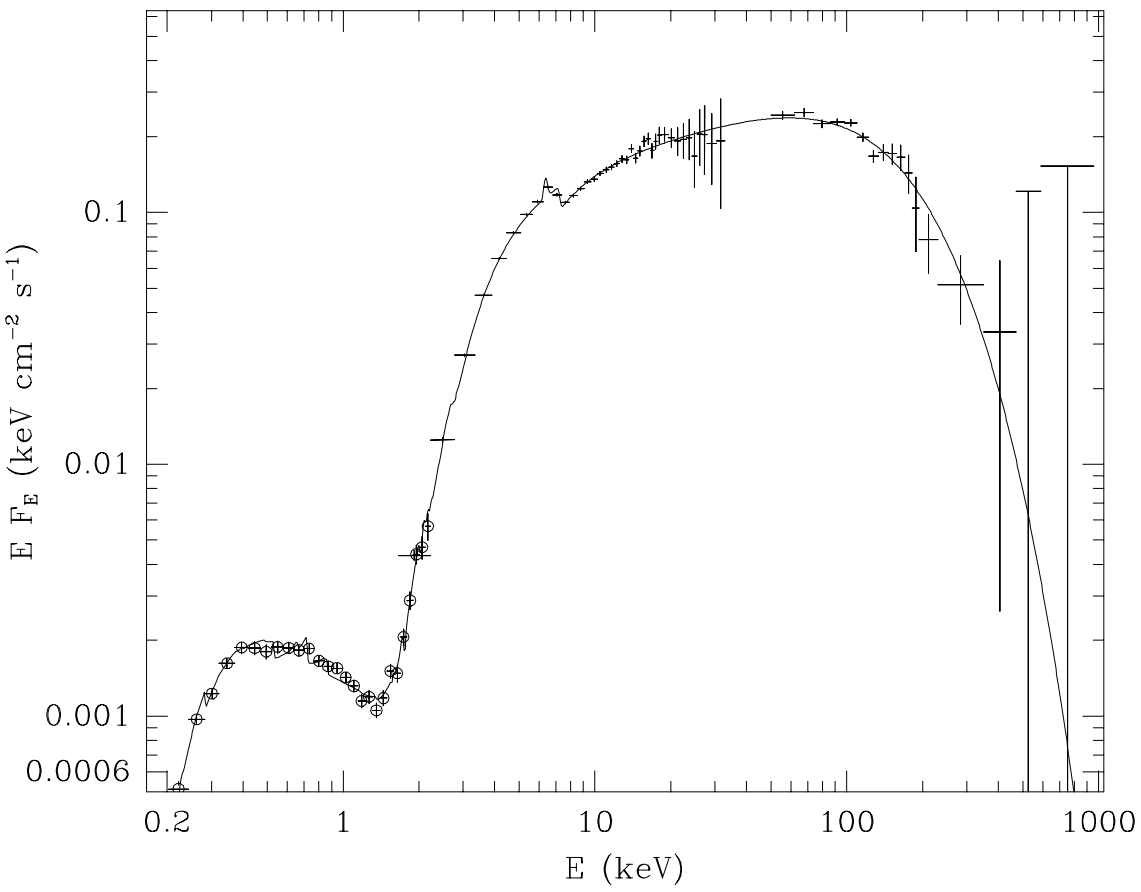

Figure 1: The spectrum observed by OSSE, 1991 June 29–July and by *Ginga* (Yaqoob et al. 1993) and *ROSAT* (marked by circles, Warwick, Done & Smith 1995), 1991 May 31–June 1. The solid curve represents a thermal Comptonization model with $kT = 66$ keV and $\alpha = 0.65$ absorbed by an ionized medium, and with addition of a soft excess.

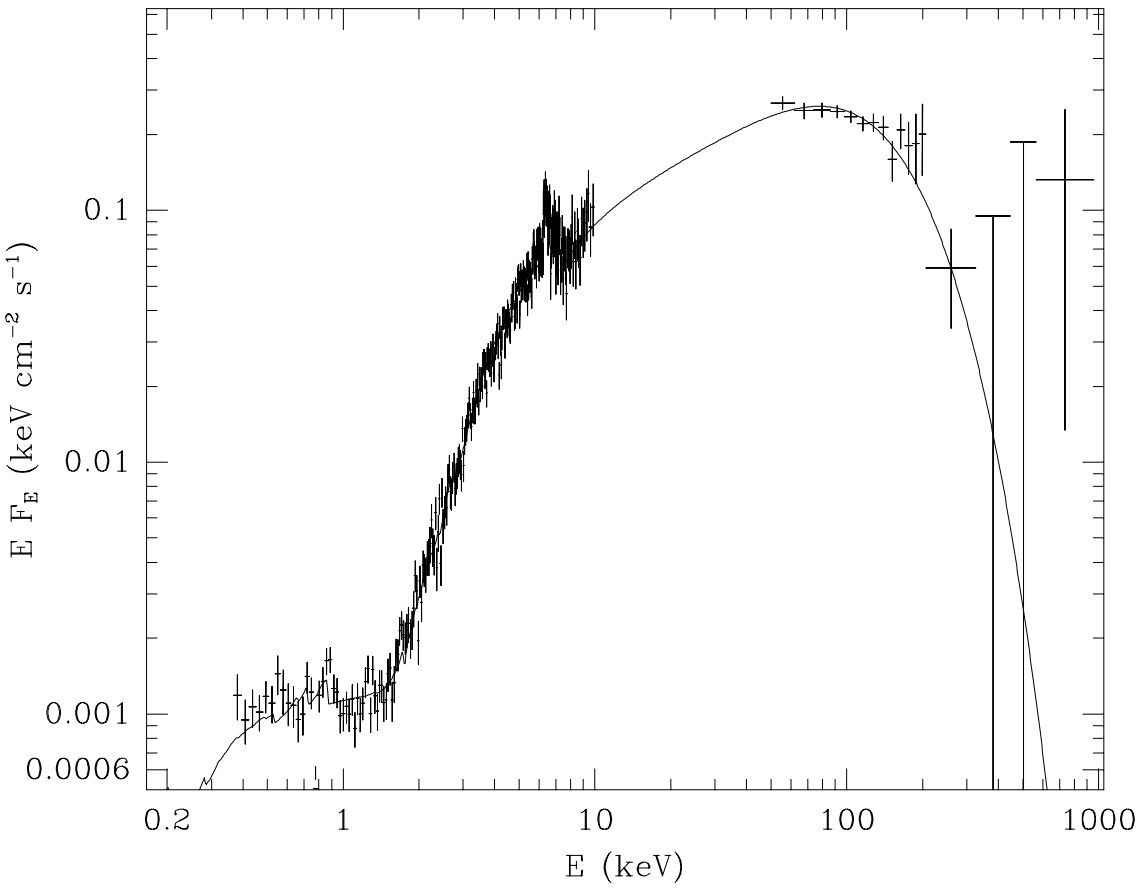

Figure 2: The spectrum observed by OSSE, 1993 May 24–31, and by *ASCA*, 1993 May 25. The solid curve represents a thermal Comptonization model with $kT = 47$ keV and $\alpha = 0.44$ absorbed by an ionized medium, and with addition of a soft excess.

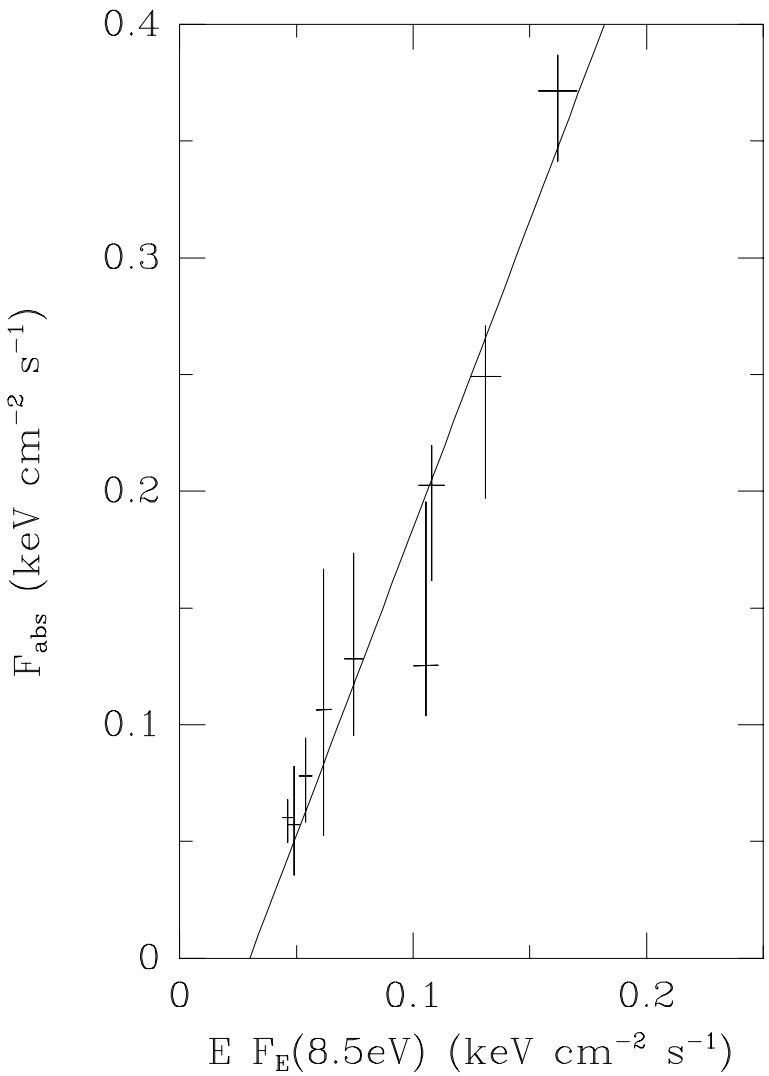

Figure 3: Comparison of the prediction of the transmission model with the $IUE/EXOSAT$ data. The crosses give the flux F_{abs} absorbed by the cold matter in the line of sight obtained from $EXOSAT$ data, and $EF_E(8.5\text{eV})$ from IUE. The solid line gives $EF_E(8.5\text{eV})$ as a function of F_{abs} from the transmission model.

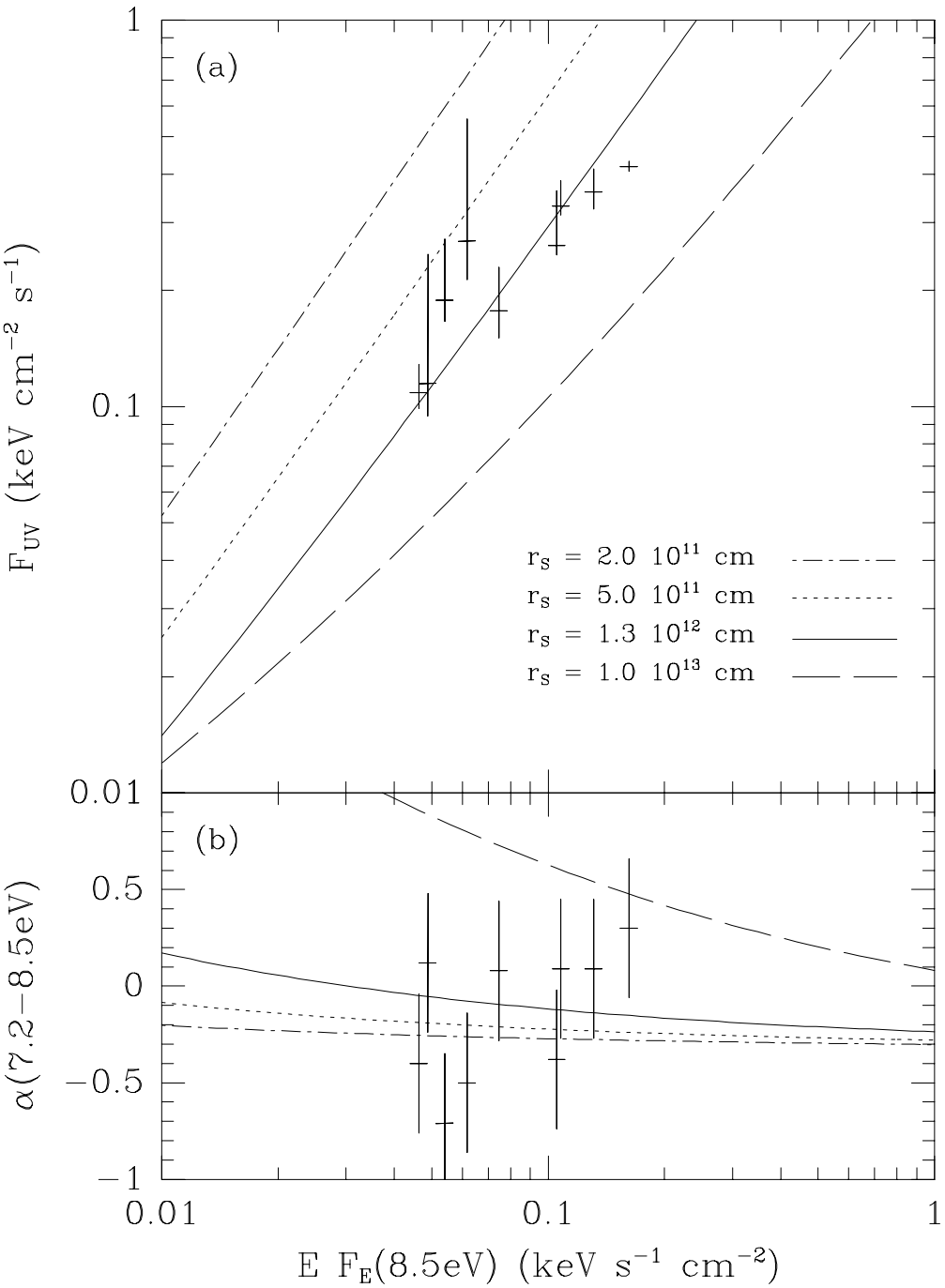

Figure 4: Comparison of the predictions of the reflection model with the data. (*a*) Crosses give the total UV flux F_{UV} from reemission of the absorbed X-γ flux as obtained extrapolating the *EXOSAT* X-ray power laws to γ-rays assuming thermal Comptonization at $kT = 60$ keV, and $R = 0.5$. The curves relate the total F_{UV} to EF_E(8.5eV), as predicted by the disk spectrum for various Schwarzchild radii r_S. (*b*) Crosses give the UV spectral indices (Ulrich et al. 1991). Curves give the indices predicted by the disk-corona model.