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WEAK SOFT X-RAY EXCESSES NEED NOT RESULT FROM THE HIGH-FREQUENCY TAIL OF THE OPTICAL/ULTRAVIOLET BUMP IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The broad-band *ROSAT*/*EXOSAT* X-ray spectra of six Seyfert 1 galaxies are fitted by a model consisting of a direct power law and a component due to reflection/reprocessing from a partially ionized, optically thick medium. The reflected spectrum contains emission features from various elements in the soft X-ray range. In all objects but one (Mrk 335), the fit is satisfactory, and no additional soft X-ray excess is required by the data. This means that in most sources there is no need for the thermal "big blue bumps" to extend into soft X-rays, and the soft X-ray excesses reported previously can be explained by reflection/reprocessing.

Satisfactory fits are obtained for a medium ionized by a source radiating at $\lesssim 15\%$ of the Eddington rate. The fits require that the reflection is enhanced relative to an isotropically emitting source above a flat disk. The necessary high effectiveness of reflection in the soft X-ray band requires strong soft thermal flux dominating over hard X-rays.

Subject headings: accretion, accretion disks — atomic processes — galaxies: active — X-rays: galaxies

1. INTRODUCTION

Two spectral components dominate emission from unobscured active galactic nuclei (AGNs) in the optical/UV/X-ray range: the so-called big blue bump (extending from the optical/UV to either the extreme ultraviolet [EUV] or soft X-rays) and a hard X-ray power law (e.g., Bregman 1990). Models of the nuclear activity strongly depend on the spectral shape of the big bump and the relative strength of these two spectral components. Therefore, observational determination of the extension of the big blue bump into soft X-rays is of extreme importance.

The first suggestions about the thermal character of the big bump and its connection to an accretion disk surrounding a massive black hole (Shields 1978; Malkan & Sargent 1982; Malkan 1983) referred to the optical/UV spectral region. However, in the case of many high-redshift quasars, the big bump spectrum continued in the rest frame far into the UV without any significant break (Bechtold et al. 1984; Reimers et al. 1992). This implied that the big bump, at least in some objects, extends far into the unobserved EUV band.

The suggestion that the big bump actually extends into soft X-rays was made by Arnaud et al. (1985) for Mrk 841. In this object, the soft X-ray flux below ~2 keV is significantly higher than that predicted by the extrapolation of the hard X-ray power law. Such soft X-ray excesses were subsequently found to be common in AGNs. Wilkes & Elvis (1987) reported weak soft X-ray excesses below 0.3 keV in ~50% of 33 *Einstein* quasar spectra. Similarly, sources with soft X-ray excesses constituted ~50% of all the unobscured AGNs in the *EXOSAT* sample of Seyfert galaxies (Turner & Pounds 1989).

The nature of the soft X-ray excesses has usually been explained as a high-frequency tail of accretion disk spectra (e.g., Czerny & Elvis 1987; Ross, Fabian, & Mineshige 1992), although some doubts concerning the detailed comparison of the model with data still existed, based on polarimetry observations and measurements of the Lyman edge.

However, a considerable difficulty with the disk emission model of soft X-ray excesses appears when the statistical aspect of the model is considered. This difficulty is seen most clearly in a recent study of the *ROSAT* data on 58 Seyfert 1 galaxies by Walter & Fink (1993, hereafter WF). They have found that 90% of Seyfert 1 galaxies have soft X-ray excesses appearing below ~0.4 keV. Furthermore, the strength of the excess is well correlated with the UV part of the big bump. The authors thus conclude that the shape of the big bump is universal, and only its amplitude varies from one object to another by a factor of 100 in comparison with the underlying continuum.

None of the models of the big bump suggested so far predict the same spectral shape for sources covering a few orders of magnitude in luminosity, as is the case in the sample of WF. In particular, the universal shape of the big bump cannot be explained within the framework of the accretion disk theory, since the range of accretion rates and black hole masses required by the range of luminosities would lead to a large dispersion in the high-frequency extension of the big bump (WF). Therefore, a verification of the connection of soft X-ray excesses to the big bump is truly essential.

It has been suggested (Turner et al. 1991) that weak soft X-ray excesses may actually be due to the presence of various emission lines unresolved by current detectors. In fact, the presence of the Compton hump and the Fe Kα line in *Ginga* data indicate strong irradiation of cold gas by hard X-rays (Pounds et al. 1990; Nandra 1991). Reflection/reprocessing by partially ionized medium leads to formation of a complex X-ray spectrum (Netzer 1993; Ross & Fabian 1993; Życki et al. 1994, hereafter ZKZK). Ross & Fabian (1993) have actually suggested that the presence of the reflected component may account for the observed soft X-ray excesses.

In this *Letter* we show the results of fitting the composite X-ray spectrum, consisting of the direct power-law component and the component reflected/reprocessed by partially ionized medium predicted by the model of ZKZK, to the broad-band *ROSAT*-*EXOSAT* data for six Seyfert 1 galaxies with low Galactic absorption column. In all cases but Mrk 335, the spectrum is well fitted by the model *without* any additional soft X-ray spectral component. Thus, in most objects the presence of the soft X-ray excesses may be attributed to reprocessing,

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and the universal form of the excesses may be explained by atomic physics.

2. THE SPECTRAL MODEL AND FITS TO THE *ROSAT/EXOSAT* DATA

The aim of this *Letter* is to test the possibility that the X-ray reflection/reprocessing alone can produce many of the observed soft X-ray excesses. Model X-ray spectra are calculated using a code developed by ZKZK. The model assumes that the primary X-ray radiation, which is a power law extending up to 100 keV, illuminates a semi-infinite slab of gas causing its partial ionization. A fraction of the incident photons gets reflected due to Compton scattering, and the remainder is absorbed. However, a substantial fraction of the absorbed hard X-ray flux is reemitted in the soft X-ray band in the form of emission lines and continua. The code uses a Monte Carlo technique for the transfer of X-rays, while the photoionization part of the calculation is based on the XSTAR code (Kallman & McCray 1982; Kallman & Krolik 1993).

The reflected spectrum (continuum and reemission features) depends both on the shape of the incoming X-ray radiation and on the ionization stage of the reprocessor. Irradiation is parameterized by the energy index of the primary power law, α ($F_E \sim E^{-\alpha}$), and the ionization parameter, ξ, defined at the slab surface as

$$\xi \equiv \frac{4\pi F_h}{N_{\rm H}}, \qquad (1)$$

where

$$F_h = \int_{100\,{\rm eV}}^{100\,{\rm keV}} F_E\,dE$$

and $N_{\rm H}$ is the hydrogen number density (assumed uniform throughout the slab).

The ionization stage of the slab is calculated assuming two components: incident X-ray photons (parameterized as above) and internally generated soft photons (blackbody at an assumed temperature, constant with depth). This additional blackbody component is not included in the spectrum model (or in the ξ definition), as required by the purpose of this work. We assume the blackbody temperature 2×10^5 K and the gas density 10^{14} cm^{-3}. An example of the model spectrum is shown in Figure 1.

We fit this model to broad-band *ROSAT/EXOSAT* data for six Seyfert 1 galaxies (see Table 1) using the XSPEC X-ray fitting package (Shaffer, Haberl, & Arnaud 1991). The *ROSAT* data for these sources have been already analyzed (Turner, George, & Mushotzky 1993a, hereafter TGM) using power-law fits.[2] Soft X-ray excesses have been reported for all of them on the basis of a comparison of the soft X-ray slope (from *ROSAT*) and the hard X-ray slope (from *EXOSAT* or the Broad Band X-Ray Telescope [BBXRT]). Better fits were generally obtained when a power law was supplemented by an emission line or an absorption edge which indicated a significant role of reprocessing (TGM).

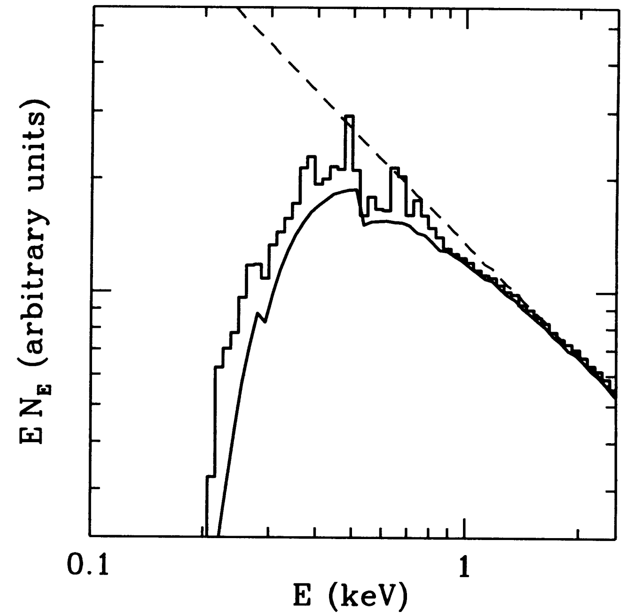

FIG. 1.—Model spectrum for Mrk 509. The dashed line gives the primary photon spectrum, which is a power law. The solid histogram and the solid curve represent the model spectrum and the primary spectrum, respectively, both attenuated by the Galactic absorption. The difference between the histogram and the solid curve represents the soft X-ray excess explained by reflection/reprocessing. The parameters are given in Table 1; see also text for model description.

We fixed the hydrogen column density $N_{\rm H}$ at the Galactic value for all the sources, and fitted the data varying the energy index of the primary component α, the ionization parameter ξ, and the weight f of the reflected component (the ratio of irradiating flux to primary flux seen by an observer).

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[2] We used the 1992 March *ROSAT* response matrix for data obtained before 1991 October, and the 1993 January matrix for data obtained after 1991 October, as suggested by Fiore et al. (1994) and T. J. Turner (private communication).

TABLE 1

EXOSAT OBSERVATIONS LOG[a] AND FITS OF REFLECTION/REPROCESSING MODEL TO THE DATA

Source	Date	Counts	Galactic $N_{\rm H}$[b]	α[c]	ξ[d]	f[e]	χ^2/dof
ESO 198−G24[f]	...	...	0.030	$0.82^{+0.17}_{-0.12}$	130^{+54}_{-23}	$2.7^{+1.2}_{-0.9}$	32/26
ESO 141−G55	306/83	40,340	0.055	$0.93^{+0.08}_{-0.07}$	300^{+35}_{-76}	$2.4^{+0.6}_{-0.5}$	58/40
MCG −2-58-22	321/84	51,770	0.034	$0.80^{+0.06}_{-0.04}$	160^{+44}_{-31}	$1.8^{+0.3}_{-0.4}$	69/49
NGC 7469	332/84	67,750	0.048	$0.90^{+0.06}_{-0.03}$	460^{+170}_{-140}	$2.3^{+0.8}_{-0.5}$	63/47
Mrk 509	295/83	31,030	0.042	$1.03^{+0.05}_{-0.06}$	74^{+97}_{-47}	$1.2^{+0.4}_{-0.2}$	41/35
Mrk 335	334/85	35,090	0.040	1.1	79	2.8	465/70

NOTE.—Errors represent 90% confidence limits for one interesting parameter.

[a] Details of *ROSAT* observations are given by TGM.

[b] In units of 10^{22} cm^{-2}; column density of cold absorbing material was fixed at the Galactic value for each object.

[c] Energy spectral index; the maximum considered value is 1.1.

[d] Ionization parameter.

[e] Relative weight of the reflected component.

[f] Only *ROSAT* data were fitted.

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Results presented in Table 1 show that, with the exception of Mrk 335, the fits are statistically acceptable with $\chi^2/\mathrm{dof} = 1.2$–$1.4$, i.e., the quality of fits is comparable to or better than the fits to the *ROSAT* data alone with a single power law (TGM). An example of fits is shown in Figure 2.

The best-fit values of f are somewhat larger than found previously on the basis of *Ginga* data by Nandra (1991). However, the reflection model used by Nandra (1991) assumed neutral gas opacities. The "hump" in the spectrum reflected from partly ionized medium is less prominent above the direct part than the analogous "hump" in the neutral reflection model. That is due to a smaller ratio of opacities at ~2 and ~10 keV when comparing the ionized and neutral reflector cases (Lightman & White 1988). Therefore, if a *Ginga* spectrum can be fitted by neutral medium reflection with a given f, it is likely to be fitted also by ionized reflection with a higher f. An example of this is the analysis of combined (nonsimultaneous) *ROSAT*/*Ginga* data of NGC 7469 (Leighly et al. 1994). The data can be fitted very well by our model with $f = 1.7$ or $f = 2.3$ (depending on the *Ginga* data set), including the iron line near 6.5 keV. The observed equivalent width (EW) of the iron Kα line (~140 eV; Nandra 1991), often quoted as the confirmation of neutral flat disk (i.e., without any enhancement) reflection (George & Fabian 1991), may also agree with our enhanced reflection if we notice that the angle-averaged value of EW (used for consistency with the continuum used) is smaller than in the face-on model. Życki & Czerny (1994) find EW $\approx$ 70 eV for the viewing angle $\theta_f = 60°$ in the broad range of accretion rates of "α"-disk (integrated over the whole disk; see their Fig. 19). Theoretical justification of enhanced reflection was given by Ghisellini et al. (1991) and Rogers (1991).

Low absorption opacities required for efficient reflection result partly from ionization caused by the blackbody spectral component. For the assumed blackbody temperature (2×10^5 K) and the best-fit values of ξ (100–300), the ratio of UV to X-ray luminosities is in the range 30–100, while the observed ratio is of the order of a few. This inconsistency may imply the need for thorough description of radiative transfer of soft photons. Such a treatment is likely to produce stronger ionization, hence lower opacity and more efficient reflection, and thus the required blackbody temperature is likely to be lowered. Also, because the thermal radiation partially accounts for the viscous flux diffusing from the disk, its spectral shape is actually that of a Wien spectrum (saturated Comptonization), with a certain dilution factor which would reduce the emergent L_{UV}. Ross & Fabian (1993) get the dilution factor $(2.5)^4 \approx 40$, which means that the normalization of the blackbody may be actually smaller, provided that it is high enough to give the required ionization. We note that the current version of the ZKZK code as used here suffers from problems with thermal balance calculations and probably underestimates the temperature. Further research with the improved code has to be done to resolve the above problems definitely.

We thus conclude that the spectral shape observed by *ROSAT* and *EXOSAT*—with the excess of the soft X-ray flux above the extrapolated hard X-ray power law exhibiting spectral structure in the form of emission features (TGM)—can be explained by the presence of the strong reflected component arising from matter that is partially ionized. With the exception of Mrk 335, the presence of an additional soft component is *not* required by the data.

3. DISCUSSION

The satisfactory fit of both the soft and hard X-ray data for five out of six Seyfert 1 galaxies by the composite power-law/reflection spectrum from partially ionized gas shows that we do not necessarily see the soft X-ray tail of the big bump in these sources, contrary to the opinion prevailing so far. However, strong soft X-ray excess due to an additional spectral component is required in Mrk 335 (see also Turner et al. 1993b) as well as in Mrk 841; the soft excesses in these objects cannot be explained by our model. Clearly distinctive variability patterns in the soft and hard X-rays in Mrk 841 (George et al. 1993) and Mrk 335 (Turner & Pounds 1988) indicate that in those sources another component not directly related to the hard X-ray source (most likely a big bump tail) contributes strongly to the soft X-ray emission. Weak soft X-ray excesses reported previously in Seyfert galaxies and quasars (Wilkes &

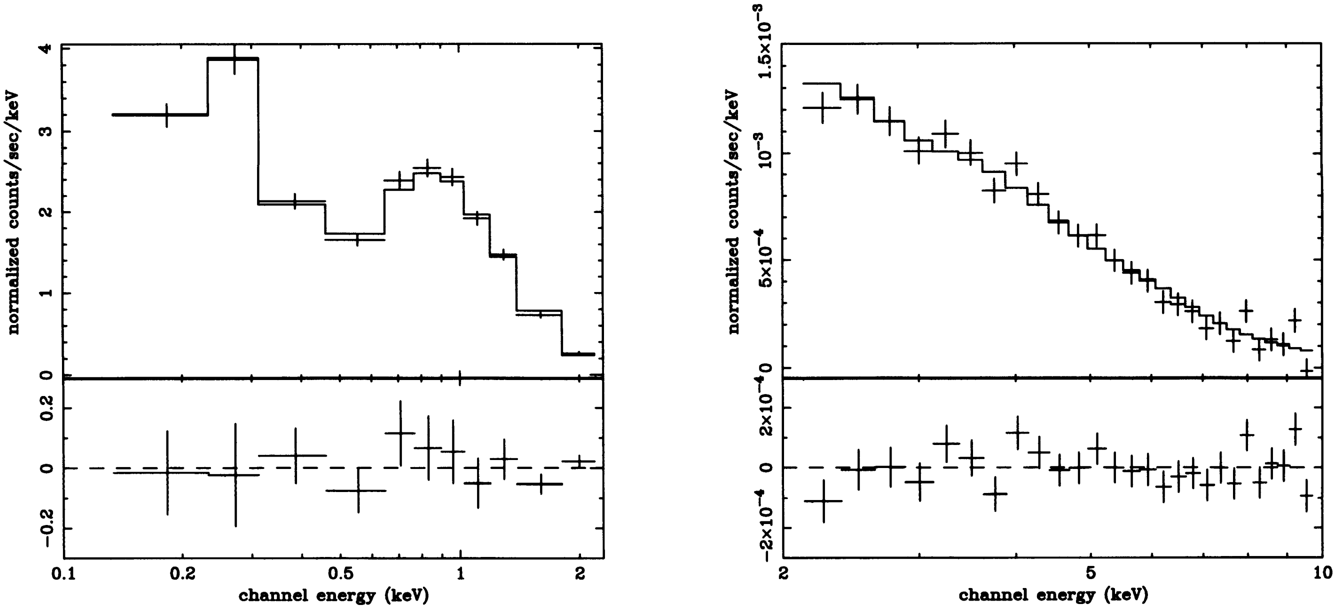

FIG. 2*a* FIG. 2*b*

FIG. 2.—Best fit of the reflection/reprocessing model folded through the response of the corresponding detector (*upper panels*), and data minus model residuals (*lower panels*) for (*a*) *ROSAT* and (*b*) *EXOSAT* observation of Mrk 509. Model and fit parameters are given in Table 1.

Elvis 1987; WF) appear to be due to the spectral features accompanying reflection of X-rays from partially ionized gas.

The correlation between the UV bump and the soft X-ray excesses reported by WF is interpreted in our model as an overall correlation between the UV and the reflected X-ray component. It may indicate similar inclination effects for the big blue bump and the reflected X-ray component, as expected in the case of both components being emitted by the accretion disk.

The sensitivity of the data to a model is high enough to give in principle the correct estimate of the ionization stage of the reflecting gas. Therefore, further refinements of the model are necessary. They may reduce the temperature and the bolometric luminosity of the blackbody required to ionize the medium and enhance allowed X-ray illumination, thus leading to a self-consistent picture with the blackbody contribution limited to the UV and EUV range. The best illustration of the sensitivity of the model to the assumptions is the difference by two orders of magnitude in the predicted value of the ionization parameter ξ between the model with emission lines (this *Letter*) and without them (recombination continua only; Czerny et al. 1993). The first refinement should be via the improved description of the vertical structure of the slab, possibly including a gradient in a soft thermal flux and ionization by relativistic particles suggested by M. Sikora (private communication). The second step will include the integration over a range of ionization parameters, as predicted by a global geometrical model. In the case of an accretion disk, Doppler shifts also have to be included.

The identification of numerous weak soft X-ray excesses with reprocessing features instead of the big bump tail means that the soft X-ray data in these objects do not give real extension of the big bump into high frequencies. The turnoff in the far-UV observed in some Seyfert galaxies (Edelson & Malkan 1986) may be intrinsic, and not necessarily caused by extinction along the line of sight. Therefore, the X-ray data for these sources put only upper bounds on the bolometric luminosity of the big bump, contrary to current opinion.

The lack of luminosity constraints makes it more difficult to distinguish between the two big bump models: thermal emission from an accretion disk and thermal emission from optically thick clouds. The requirement of enhanced reflection can be fulfilled both in disk models through anisotropy of Compton scattering and in cloud models through a larger covering factor (where it seems to be more natural). However, we should interpret with caution particular numerical values of such fit parameters as α or f, since the current model is still very much simplified: it describes reflection from a ring of disk which can be characterized by a single value of ξ. If such an enhanced reflection is really necessary, it will imply that the reflection "hump" should be more prominent when observed in the 30–100 keV range, because its "blue side" does not depend on ξ.

We can compare the required range of the ionization parameter with predictions for a standard α viscosity accretion disk around a massive black hole (Shakura & Sunyaev 1973). If we assume that the irradiating X-ray flux is of the same order as the viscous flux dissipated locally in the disk and the X-ray source is located at a distance of 20 gravitational radii above the disk (so most of the reprocessing is within some 50 gravitational radii from the black hole), then the ionization stage in these parts of the disk is effectively characterized by $\xi \lesssim 100$ for the disk luminosity lower than 15% of the Eddington luminosity, independent of the mass of the black hole (Matt, Fabian, & Ross 1993; Życki & Czerny 1994). In this picture, spectral features due to reprocessing (soft X-ray hump, Compton hump, and Fe Kα line) are expected to be delayed with respect to the primary power law by a few thousand seconds; the delay time depends on the value of the mass of the central black hole. Also, the shape of the Compton hump is different from that expected from completely neutral gas.

Further research is needed to give strong support to any of the two models of reprocessing.

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