TESTING COMPTONIZATION MODELS USING BeppoSAX OBSERVATIONS OF SEYFERT 1 GALAXIES

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Received 2000 December 18; accepted 2001 April 9

ABSTRACT

We have used realistic Comptonization models to fit high-quality BeppoSAX data of six Seyfert galaxies. Our main effort was to adopt a Comptonization model taking into account the anisotropy of the soft photon field. The most important consequence is a reduction of the first scattering order, which produces a break (the so-called anisotropy break) in the outgoing spectra. Thus, anisotropic Comptonization models yield spectra with convex curvatures. The physical parameters of the hot corona (i.e., the temperature and optical depth) obtained by fitting this class of models to broadband X-ray spectra are substantially different from those derived by fitting the same data with the power law + cutoff model commonly used in the literature. In particular, our best fits with Comptonization models in slab geometry give a temperature generally much larger and an optical depth much smaller than those derived from the power law + cutoff fits, using standard Comptonization formulae. The estimate of the reflection normalization is also larger with the slab corona model. For most objects of our sample, both models give Compton parameter values larger than expected in a slab corona geometry, suggesting a more “photon-starved” X-ray source configuration. Finally, the two models provide different trends and correlation between the physical parameters: for instance, with the power law + cutoff fits, we obtain a correlation between the reflection normalization and the corona temperature, whereas we find an anticorrelation between these parameters with the slab geometry. These differences have major consequences for the physical interpretation of the data. In the framework of reprocessing models, the cutoff power-law best-fit results suggest that the thermal corona is dominated by electron-positron pairs. On the contrary, the slab corona model is in better agreement with a low pair density solution.

Subject headings: galaxies: active — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

The broadband X-ray spectra (2–300 keV) of Seyfert 1 galaxies are generally well fitted by a cutoff power-law continuum with superimposed secondary components, such as a neutral iron line and a reflection hump. The latter components were detected at the end of the 1980s with Ginga (Piro, Yamauchi, & Matsuoka 1990; Matsuoka et al. 1990; Pounds et al. 1990) and are considered to be signatures of reprocessing of the primary X-ray emission in the surrounding cold matter. A high-energy cutoff in the X-ray/γ-ray part of the spectrum was first unambiguously detected by SIGMA and OSSE in NGC 4151 (Jourdain et al. 1992; Maisack et al. 1993). A high-energy cutoff was also required to fit the average X-ray/γ-ray spectra (obtained from data of different satellites) of a sample of Seyfert galaxies (Zdziarski et al. 1995; Gondek et al. 1996). The broadband capabilities of the Italian-Dutch satellite BeppoSAX permitted detection of high-energy cutoffs in other Seyfert 1 galaxies, about half of the 15 observed with this satellite. Values of the high-energy cutoffs range from 70 to ~300 keV (Matt 2000, hereafter M00).

A cutoff power law plus reflection model (the so-called PEXRAV model in XSPEC; Magdziarz & Zdziarski 1995) depends on three parameters: the spectral index Γ, the high-energy cutoff $E_c$, and the reflection normalization $R$, the former characterizing the shape of the primary continuum. The physical interpretation of these parameters is generally undertaken in the framework of the thermal Comptonization mechanism, which is commonly believed to be the origin of the X-ray emission of Seyfert galaxies. Using approximate relations (§ 4), it is then possible to derive, from values of $Γ$ and $E_c$, values of the temperature $kT_e$ and optical depth $τ$ of the “Comptonizing” hot plasma (the so-called “corona”).

If such approximations are sufficient in isotropic geometries (e.g., a central soft photon source surrounded by a spherical hot cloud), where the Comptonization process produces roughly power law spectra with high energy cutoffs, strong discrepancies may appear in anisotropic ones, especially for small optical depth and large temperature. Indeed, the (possible) anisotropy of the source of seed photons (as seen by the corona) may introduce anisotropies and modifications of the outgoing spectrum. The largest effect occurs when soft photons are emitted by a plane (disk) below the corona. In this case, photons backscattered toward the disk in the first scattering are necessarily produced in “head–on collisions” and therefore have an energy gain larger than average, while photons scattered toward the corona (i.e., in the forward direction) have an energy gain smaller than average. As a consequence, the contribution of the first scattering order to the outgoing flux is significantly reduced, producing a spectral break (the so-called “anisotropy break”) in the spectrum. Below the high-energy cutoff, the spectra are then better described by broken power laws than by a simple power law, contrary to what is generally believed (Petrucci et al. 2000, hereafter P00). However, these anisotropic effects become less impor-
tant for larger optical depth (i.e., $\tau > 1$), since they are “smoothed” by the larger number of Compton scatterings suffered by the soft photons.

It is also worth noting that the energy of the anisotropy break, which is, in practice, close to the peak energy of the third scattering order (Haardt 1993), depends on $kT_e$ but also on the temperature of the seed soft photon plasma, $kT_{bb}$. Consequently, if in the case of isotropic geometry the spectral shape is relatively independent of $kT_{bb}$, which fixes only the low-energy boundary of the emitted spectrum, in anisotropic geometry the shape of the Comptonization spectra depends on it.

In a recent paper (P00), we have applied accurate Comptonization models to fit high-quality data of the BeppoSAX long look at NGC 5548. We have underlined the importance of the anisotropic effects and, in particular, we have shown that because of the presence of the anisotropy break, above which the intrinsic continuum is steeper, the temperature of the hot electrons estimated from Comptonization models in anisotropic geometry can be much larger that the one derived by fitting the data with a power-law + cutoff model.

We have also shown that these different models may provide different (and even opposite) relationships between physical parameters. For instance, still in the case of NGC 5548, the spectral softening of the spectrum, observed during a small flare in the central part of the observation, correlates with an increase in the high-energy cutoff (i.e., of the corona temperature) in the case of PEXRAV, but with a decrease of the corona temperature when using an anisotropic Comptonization model.

In the same spirit of P00, we extend our application of accurate Comptonization models to a larger sample of objects. We report in this paper the results of this study. The paper is organized as follows. In §2 we briefly present the main results of the BeppoSAX observations of Seyfert galaxies. We also present the sample of objects used. We describe the models and the fitting procedure in §3. We also detail in this section the fit of the soft excess/warm absorber (hereafter WA) features observed in each object. We present the results of the fits in §4 and discuss their physical interpretations in §5. We then conclude in the last section.

2. THE DATA

2.1. Overview of the BeppoSAX Observations of Seyfert 1 Galaxies

Two major BeppoSAX Core programs were devoted to classical Seyfert 1 galaxies with the aim of studying the broadband spectra (PI: G.C. Perola) and spectral variability (PI: L. Piro). Thirteen sources have been observed in aggregate so far since the launch of the satellite in 1996.

Reviews summarizing the main results for these sources have been presented by Piro et al. (2000b) and M00. For all objects, the spectral models used by the authors include a power law with exponential cutoff (i.e., $f_\nu \propto E^{-\gamma} e^{-E/\Gamma}$) characterized by a photon index $\Gamma$ and an $e$-folding energy $E_\nu$, a Gaussian to fit the neutral iron line near 6.4 keV, and a Compton reflection continuum characterized by a reflection normalization $R$. Soft excess and/or WA features were added if required by the data.

The major findings are as follows:

1. A high-energy cutoff is generally observed, with an $e$-folding energy typically in the range 70–300 keV.

2. All sources show the presence of a reflection component, confirming the Ginga and ASCA results (Nandra & Pounds 1994).

3. Only two objects (Mrk 509 and Mrk 841) show the presence of a soft excess. This sharply contrasts with the results obtained with EXOSAT (Turner & Pounds 1989) and ROSAT (Walter & Fink 1993), where most of the Seyfert 1 observed seemed to show such excess (for a discussion of this point see Piro, Matt, & Ricci 1997). On the other hand, WA features (mostly the O vii and O viii edges) are generally observed in the LECS range.

4. A correlation between the power-law index $\Gamma$ and the amount of reflection component $R$ is indicated, in the same sense as found by Zdziarski, Lubinski, & Smith (1999, hereafter Z99). However, the issue of the reality of this correlation is still open, since it may be due to the fact that the two parameters are strongly related in the fitting procedure (see, e.g., Vaughan & Edelson 2000).

2.2. Our Sample

From the sample of Seyfert 1 galaxies observed by BeppoSAX, we have selected observations with good signal-to-noise ratios (S/N) at high energies as measured with the PDS instrument. We therefore favored objects with hard X-ray spectra. Such observations are best suited to an analysis of the high-energy spectra.

The subsample of objects studied in this paper is reported in Table 1, with the name of the different objects, the date of the BeppoSAX observations (some of these objects have been observed several times), the exposure time, and the statistical significance in the PDS instrument. We also present results from the observation of ESO 141-G55, even if its detection in the PDS instrument is relatively weak, since this source was recently observed for the first time by BeppoSAX.

NGC 4151 was observed three times by BeppoSAX, twice in 1996 during the SV phase (in July and in December), and once in January 1999 during A02. However, during the observation of 1996 July, the source experienced a strong increase of the 2–10 keV flux by a factor of 2 on timescales of 1 day, with significant spectral variability, as shown by Piro et al. (2000a). Following to these authors, we choose to study separately the low and high states occurring during this period (indicated as 1996L and 1996H below). Unfortunately, during the high state, the LECS was o\textup{f}. Therefore, only the MECS and PDS data are available for this state. In this paper we have not used the observation of 1996 December, since it does not differ substantially from the low state of 1996 July.

Concerning Mrk 509, its observation has been split into two parts during the AO2. Since no significant spectral variability was observed between the two data sets (Perola et al. 2000), we only refer here to the combined spectrum.

In this paper we are concerned with data from three of the four instruments on board BeppoSAX: the Low Energy Concentrator Spectrometer (LECS; Parmar et al. 1997), covering the 0.15–10 keV range; the Medium Energy Concentrator Spectrometer (MECS; Boella et al. 1997), covering the 2–10 keV range; and the Phoswich detector system (PDS; Frontera et al. 1997), covering the range 13–200 keV. Because of some problems that remain in the spectral analysis of LECS data above 4 keV, we use only data in the range 0.1–4 keV.
LECS and MECS event files and PDS pha files were downloaded from the BeppoSAX SDC archives. The spectral counts were extracted from a circular region of 4’ and 8’ radius around the source centroid in the MECS and LECS images, respectively. We used the data of the three (or two, for observations done after 1997 May) MECS units merged together to increase the S/N. In XSPEC (Arnaud 1996), we use the last updated responses (1997 September) and background matrices of each instrument.

3. MODEL FITTING

3.1. The Primary Continuum

We fit the data using two different models for the primary continuum: (1) an exponentially cut off power law plus a reflection component from neutral material (PEXRAV model of XSPEC; Magdziarz & Zdziarski 1995) and (2) a thermal Comptonization spectrum from a disk + corona configuration in slab geometry. The latter was obtained using the code of Haardt (1994; hereafter we refer to this anisotropic Comptonization code as AC2). This code derived the angle-dependent spectra of the disk-corona system using an iterative scattering method, where the scattering anisotropy was taken into account only in the first scattering order. It also includes a reflection component described following White, Lightman, & Zdziarski (1988) and Lightman & White (1988) and assuming neutral matter. The spectral shape of the reflected photons is averaged over angles. It is multiplied by a first normalization factor that depends on the inclination angle (see Ghisellini, Haardt, & Matt 1994 for details). In addition, the usual R normalization is left free to vary in the fitting procedure, so that for the given inclination angle, \( R = 1 \) corresponds to a solid angle, subtended by the reflector, of \( 2\pi \). We do not apply Comptonization models for other geometries (e.g., hemisphere), since, as shown for NGC 5548 (P00), the results closely follow those obtained with the slab geometry.

The fit parameters of AC2 are the temperature of the corona \( kT_c \), its optical depth \( \tau \), the temperature of the disk \( kT_{\text{disk}} \) (assuming a blackbody soft emission), and the reflection normalization \( R \). On the other hand, the PEXRAV continuum depends only on three parameters: the \( e \)-folding energy of the cutoff power law \( E_c \), the photon index \( \Gamma \), and the reflection normalization \( R \).

3.2. Soft X-Ray Excess and Warm Absorber

Most of the objects present WA features and/or a soft excess in the low part (i.e., in the LECS energy band) of their spectra. Good and realistic fits require us to take these features into account. Detailed analyses of these different components are, however, beyond the scope of this paper, which is instead focused on the high-energy continuum of the sources. Then, as a first approximation, we have added simple components (edges, Gaussian, blackbody, etc.) to the primary continuum to reproduce the main features present in the soft part of the spectra. We briefly discuss the case of each source below.

3.2.1. NGC 4151

The BeppoSAX data of NGC 4151 have already been analyzed by Piro et al. (2000a, 2000b), assuming a simple cutoff power law for the primary underlying continuum. A prominent soft excess, known to exist in this object (Holt et al. 1980) below the \( \sim 2 \) keV cutoff due to a high absorbing column, is clearly detected in the observations of 1996L and 1999. It is generally modeled by allowing some fraction of the central source to be completely uncovered or viewed through a lower column (the so-called “leaky absorber”). In addition, there is evidence of a possibly separate soft excess component that does not vary with the 2–10 keV continuum (Pounds et al. 1986; Perola et al. 1986). Part of this emission comes from an extended X-ray region known to exist in this object (Elvis, Briel, & Henry 1983; Morse et al. 1983); this emission comes from an extended X-ray region known to exist in this object (Elvis, Briel, & Henry 1983; Morse et al. 1983). Recent Chandra observations with the High-Energy Transmission Grating Spectrometer have revealed detailed spectra of this source (Ogle et al. 2000) and allow for the first time precise measurements of the ionization, temperature, and kinetics of the extended soft X-ray emission region.

For the scope of the present paper, we model the complex soft X-ray emission in a (relatively) simpler manner. Following Piro et al. (2000a, 2000b), we have used a dual absorber; that is, the source is covered completely by a medium with a column density \( N_{\text{H}} \) and with a covering fraction \( f_{\text{cov}} \), by a second medium with a column density \( N_{\text{H,cov}} \). On the other hand, the soft excess below 2 keV was modeled by a scattering component plus an ultrasoft component described by a thermal bremsstrahlung, both absorbed by the Galactic column density.
Because of the lack of LECS data for the high state of 1996, we cannot constrain the different components of the soft X-ray range. We thus analyze the data only above 3.5 keV, adding a simple photoelectric absorption characterized by a column density \( N_{\text{HI}} \).

We report in Table 2 for the three observations our best-fit parameters \( N_{\text{HI}} \), \( N_{\text{H, cov}} \), and \( f_{\text{cov}} \) obtained with PEXRAV to model the continuum. We note a significant increase of \( N_{\text{HI}} \) between 1996L and 1999. As already noted by Piro et al. (2000, 2001), such variations suggest that the structure of the dual absorber has slightly changed between the two observations.

### 3.2.2. NGC 3783

Evidence for deep absorption features in the 0.1–1.5 keV band of NGC 3783 has already been detected by ROSAT (Turner et al. 1993b) and *ASCA* observations (George et al. 1995), the main ones being the O vii and O viii edges at 0.74 and 0.87 keV, respectively. More recently, in 2000 January, NGC 3783 was observed using the High-Energy Transmission Grating Spectrometer on the *Chandra* X-ray observatory (Kaspi et al. 2000). These authors detected a large number of emission and absorption lines, strongly confirming the presence of warm absorbing/emitting media embedding the central X-ray source.

An emission feature near 0.5 keV has also been claimed in *ASCA* spectra of this source (George et al. 1998) and has been interpreted as an O vii emission line (expected at 568 eV). Kaspi et al. (2000) clearly see this emission feature in the *Chandra* spectra, confirming for the first time the detection of this component.

According to these results, we have included in our models two absorption edges, near 0.74 and 0.87 keV, and a Geanima peak near 0.5 keV to fit the O vii line. The best-fit results are reported in Table 3. As suggested by the recent *Chandra* observation, the edge near 1.3–1.4 likely corresponds to contributions by Fe L and Ne K edges, whereas the second one, centered near 0.8–0.9 keV, may be due to the O viii edge.

Concerning the line, we have checked that its addition significantly improves the fit with \( \Delta \chi^2 = 16 \) (according to the \( F \)-test, this difference implies a probability of less than 0.01 that the line is due to random fluctuations in the counts). This feature is thus detected by *BeppoSAX* with a high confidence level. The corresponding best-fit central energy of the line was \( E_{\text{line}} = 0.55 \) keV, with an EW of \( \sim 100 \) eV. Such EW is large, and it is unlikely that this emission feature was only produced by O vii emission lines. In fact, in the more extreme case in which we see the blends of the three O vii lines, we expect an EW of only 30 eV (A. De Rosa 2000, private communication). The large EW and small energy of the line we obtained could be due in part to a bad modeling of the continuum near this component.

#### 3.2.3. Mrk 509

Mrk 509 was observed by *BeppoSAX* in 1998. The observation was split into two parts during the AO2, the first one being done in 1998 May and the second one in 1998 October. As already mentioned, a hardness ratio analysis of the counts shows marginal evidence of spectral variations between the two observations. They have thus been combined, and we applied the spectral analysis to the integrated counts.

These data have already been studied in detail by Perola et al. (2000, hereafter Per00). Assuming a cutoff power-law model for the intrinsic continuum of this source, the data show at low energy the presence of additional, superimposed features due to O vii and/or O viii edges as well as a high-energy feature at 1.4 keV, possibly the O vii edge.

### Table 2

**Best-Fit Parameters from PEXRAV Model**

| Source       | \( kT_e = E_2/2 \) (keV) | \( \tau \) | \( R \) \( \left(10^{22} \text{ cm}^{-2}\right) \) | \( \chi^2 \) |
|--------------|-------------------------|--------|-----------------|---------|
| NGC 5548     | 1.59 \( ^{+0.01}_{-0.02} \) | 65 \( ^{+40}_{-15} \) | 2.2 \( ^{+0.3}_{-0.4} \) | 0.5 \( ^{+0.2}_{-0.3} \) | 0.015 \( ^{+0.002}_{-0.001} \) | 147/171 |
| IC 4329 A    | 1.84 \( ^{+0.01}_{-0.02} \) | 105 \( ^{+40}_{-20} \) | 1.1 \( ^{+0.2}_{-0.3} \) | 0.3 \( ^{+0.1}_{-0.2} \) | 0.40 \( ^{+0.02}_{-0.01} \) | 161/171 |
| NGC 4151     | 1.45 \( ^{+0.15}_{-0.05} \) | 45 \( ^{+25}_{-15} \) | 3.4 \( ^{+0.4}_{-1.4} \) | 0.01 \( ^{+0.1}_{-0.1} \) | 0.15 \( ^{+0.05}_{-0.05} \) | 177/179 |
| NGC 4151 1996L | 1.24 \( ^{+0.01}_{-0.02} \) | 30 \( ^{+3}_{-2} \) | 7.0 \( ^{+0.3}_{-0.8} \) | 0.45 \( ^{+0.12}_{-0.05} \) | 0.5 \( ^{+0.02}_{-0.01} \) | 106/83 |
| NGC 4151 1996H | 1.28 \( ^{+0.11}_{-0.01} \) | 30 \( ^{+3}_{-2} \) | 6.1 \( ^{+2.9}_{-0.7} \) | 0.2 \( ^{+0.1}_{-0.1} \) | 0.1 \( ^{+0.05}_{-0.03} \) | 61/53 |
| ESO 141-G55  | 1.97 \( ^{+0.04}_{-0.02} \) | 65 \( ^{+25}_{-15} \) | 1.4 \( ^{+0.8}_{-1.9} \) | 0.9 \( ^{+0.6}_{-1.7} \) | 0.055 \( ^{+0.005}_{-0.003} \) | 176/162 |
| Mrk 509      | 1.60 \( ^{+0.03}_{-0.02} \) | 40 \( ^{+15}_{-10} \) | 3.1 \( ^{+0.8}_{-0.9} \) | 0.7 \( ^{+0.3}_{-0.2} \) | 0.048 \( ^{+0.05}_{-0.03} \) | 163/202 |
| NGC 3783     | 1.62 \( ^{+0.01}_{-0.02} \) | 55 \( ^{+15}_{-10} \) | 2.3 \( ^{+0.4}_{-0.3} \) | 0.3 \( ^{+0.1}_{-0.1} \) | 0.093 \( ^{+0.006}_{-0.006} \) | 151/162 |

**Note.**—Shown are the photon index \( \Gamma \), the temperature \( kT_e \) and optical depth \( \tau \) of the corona, the reflection normalization \( R \) and the best-fit total (i.e., intrinsic + galactic) column density for each object. In the case of NGC 4151, the complex neutral absorber is detailed in § 3.2.1. The computation of \( kT_e \) and \( \tau \) are explained in § 4.1.

### Table 3

**PEXRAV Best-Fit Parameters for Soft X-Ray Complex of NGC 3783**

| Parameter     | Value      |
|---------------|------------|
| \( N_{\text{HI}} \left(10^{10} \text{ cm}^{-2}\right) \) | \( 0.8 \( ^{+0.5}_{-0.6} \) \) |
| \( E_{\text{line}} \) | \( 55 \( ^{+0.03}_{-0.02} \) \) |
| \( \sigma_{\text{line}} \) | \( 0.1 \( ^{+0.05}_{-0.04} \) \) |
| \( E_1 \) | \( 0.84 \( ^{+0.02}_{-0.02} \) \) |
| \( \tau_1 \) | \( 0.63 \( ^{+0.09}_{-0.07} \) \) |
| \( E_2 \) | \( 1.3 \( ^{+0.10}_{-0.07} \) \) |
| \( \tau_2 \) | \( 0.16 \( ^{+0.04}_{-0.04} \) \) |

**Note.**—Best-fit parameters of the soft X-ray complex of NGC 3783, i.e., two edges and an emission line (see text for details), obtained with PEXRAV. We also report the best-fit column density, in excess of the galactic one.

\( ^{a} \) In excess of \( N_{\text{HI, gal}} = 8.5 \times 10^{21} \text{ cm}^{-2} \).

\( ^{b} \) In keV.
strong soft excess. Per00 described the latter by a “soft” power-law component ($A_1 E^{-1}$). They then obtained a significant improvement of the goodness of the fit ($\Delta \chi^2 = 20$), with the best-fit values for $A_1$ and $\Gamma_s$ being $1.11 \times 10^{-2}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ and 2.5, respectively.

Per00 underlined the fact that the addition of this “soft” component also had the interesting effect of providing a more astrophysically sound global solution, with a reflection normalization of $R \sim 0.6$ and an iron line width of $\sigma_{Fe} \sim 0.4$ keV (compared to $R \sim 2$ and $\sigma_{Fe} \sim 3$ keV without this soft component), giving some confidence as to the correctness of the model.

Following these authors, we have added this “soft” power law to our fit, fixing $A_1$ and $\Gamma_s$ to the best-fit values given above. We also add an edge with the best-fit energy and optical depth found by Per00, i.e., $E_{\text{edge}} = 0.74$ keV, $\tau_{\text{edge}} = 0.06$.

3.2.4. ESO 141-G55

The presence of a soft excess has already been suggested for this source from ROSAT observations (Turner, George, & Mushotzky 1993a). However, the BeppoSAX data do not show any evidence of such component, nor of WA features. This could be partly due to the low S/N of this observation. Consequently, our fits were done without any additional components in the soft band other than the absorption by the Galactic column density (see Tables 2 and 4).

3.2.5. NGC 5548

The WA observed in this source has been discussed in P00 and Nicastro et al. (2000), and the reader is referred to these papers for more details. For the purpose of this work, we adopt the results of P00, who have added two edges, at $E_1 = 0.74$ and $E_2 = 0.87$ keV, to fit the oxygen absorption features observed in the LECS band. The corresponding optical depths were fixed to the best-fit values obtained with PEXRAV, i.e., $\tau_1 = 0.51$ and $\tau_2 = 0.12$, respectively.

3.2.6. IC 4329A

The X-ray spectrum of IC 4329A is known to display strong neutral absorption below 3 keV, due to a gas column about 10 times greater than the Galactic value, $N_{\text{HIgal}} = 4.5 \times 10^{20}$ cm$^{-2}$ (Elvis, Wilkes, & Lockman 1989). This gas is supposed to be associated with the disk of the host galaxy, which is oriented nearly edge-on (Petre et al. 1984).

At low energies (below 1–2 keV), ROSAT and ASCA observations have also shown evidence of two rather strong edges, one consistent with O VII and the other with O VIII (Madejski et al. 1995; Cappi et al. 1996; Reynold 1997; George et al. 1998).

The BeppoSAX observation of IC 4329A has been already analyzed by Perola et al. (1999) using PEXRAV as the primary continuum. To model the soft range of the spectrum, they added a neutral column of gas to the Galactic one, and included two absorption edges. This model gives a good fit to the data, and we adopt the same description in our fits. We fix the energy and optical depth of the two edges and the neutral column density to the best-fit values obtained by Perola et al. (1999), i.e., $E_1 = 0.73$ keV, $\tau_1 = 0.52$, $E_2 = 1.03$ keV, $\tau_2 = 0.19$, and $N_{\text{H}} = 0.38 \times 10^{22}$ cm$^{-2}$.

3.3. Fitting Procedure

Since the sample is only composed of Seyfert 1 galaxies, we expect, in the unification model framework, relatively small inclination angles. In the case of NGC 4151, there are claims of a large inclination angle ($\sim 60^\circ$; Evans et al. 1993). However, this value is rather uncertain. To reduce the length of the fitting procedure, we thus decided to fix the inclination to $30^\circ$ for all the objects of our sample (Nandra et al. 1997).

The geometrical normalization of the reflection component $R$ was permitted to vary. We recall that a value $R = 1$ corresponds to a covering factor of the cold matter to the X-ray source of $\Omega = 2\pi$, whatever the degree of anisotropy of the X-ray emission.

We added a Gaussian to reproduce the iron line complex near 6.4 keV. The central energy and width of the Gaussian were permitted to vary. An iron edge in the range 7–9 keV was also added if required by the data; that is, for NGC 4515 and NGC 3783.

We allowed the relative MECS to PDS normalization to vary by 5% around the value of 0.86 to account for the estimated systematic uncertainty (Fiore, Guainazzi, & Grandi 1999). Analogously, we left the LECS to MECS normalization free to vary over the range of acceptable values 0.7–1 (Fiore et al. 1999).

Finally, in the case of PEXRAV, we fixed the parameters of the soft excess and/or WA components (i.e., edges, line,

| Source       | $kT_e$ (keV) | $\tau$ | $kT_{\text{in}}$ (eV) | $R$ | $N_{\text{H}}$ (10$^{22}$ cm$^{-2}$) | $\chi^2$ |
|--------------|-------------|--------|----------------------|-----|----------------------------------|--------|
| NGC 5548     | 230$^{+10}_{-8}$ | 0.18$^{+0.01}_{-0.01}$ | 22$^{+3}_{-5}$ | 0.9$^{+0.1}_{-0.1}$ | 0.027$^{+0.01}_{-0.009}$ | 144/170 |
| IC 4329A     | 170$^{+10}_{-8}$ | 0.20$^{+0.01}_{-0.01}$ | 15$^{+3}_{-2}$ | 1.0$^{+0.2}_{-0.1}$ | 0.35$^{+0.02}_{-0.01}$ | 158/170 |
| NGC 4151 99 | 315$^{+8}_{-6}$ | 0.08$^{+0.01}_{-0.01}$ | 20$^{+2}_{-1}$ | 0.25$^{+0.10}_{-0.05}$ | 7.5$^{+0.5}_{-0.5}$ | 184/178 |
| NGC 4151 1996L | 170$^{+80}_{-10}$ | 0.20$^{+0.04}_{-0.10}$ | > 60 | 1.8$^{+0.9}_{-0.4}$ | 4.3$^{+0.3}_{-0.3}$ | 115/82 |
| NGC 4151 1996H | 190$^{+40}_{-10}$ | 0.18$^{+0.11}_{-0.10}$ | > 90 | 1.1$^{+0.5}_{-0.5}$ | 7.0$^{+0.5}_{-0.5}$ | 66/52 |
| ESO 141-G55 | 260$^{+30}_{-30}$ | 0.05$^{+0.01}_{-0.01}$ | 25$^{+3}_{-3}$ | 1.1$^{+0.1}_{-0.3}$ | 0.09$^{+0.02}_{-0.02}$ | 166/161 |
| Mrk 509     | 210$^{+20}_{-20}$ | 0.17$^{+0.06}_{-0.06}$ | 38$^{+7}_{-7}$ | 1.0$^{+0.4}_{-0.4}$ | 0.07$^{+0.01}_{-0.01}$ | 164/201 |
| NGC 3783    | 265$^{+15}_{-15}$ | 0.12$^{+0.03}_{-0.03}$ | 13$^{+2}_{-2}$ | 0.7$^{+0.2}_{-0.2}$ | 0.11$^{+0.07}_{-0.07}$ | 143/161 |

Note.—Shown are the temperature and optical depth of the corona $kT_e$ and $\tau$, the soft photon temperature $kT_{\text{in}}$, the reflection normalization $R$, and the best-fit total (i.e., intrinsic + galactic) column density for each object. In the case of NGC 4151, the complex neutral absorber is detailed in § 3.2.1.
soft power law) to the values presented in § 3.2. For fits with AC2, in a first step we also fixed the column density to the best-fit values obtained with PEXRAV. A second series of fits were obtained with a column density free to vary. We checked that there were no significant differences between the two sets of results (we generally obtain slightly larger column densities and changes of the soft temperature $kT_{bb}$ when $N_H$ is left free to vary). We thus only consider the best-fit results with free column density below.

For computing errors on the parameters of the primary continuum (that is, $kT_e$, $\tau$, $kT_{bb}$, and $R$ for AC2, and $E_c$, $\Gamma$, and $R$ for PEXRAV), we permitted the column density to vary but we fixed the LECS/MECS and MECS/PDS normalization, and the iron line and/or edges to their best-fit values. Throughout the paper, errors on single parameters are quoted at a confidence level of 90% (i.e., $\Delta \chi^2 = 2.7$) unless otherwise specified.

4. RESULTS

4.1. The PEXRAV Model

The best-fit parameter values obtained with the fitting procedure described above using the PEXRAV model are reported in Table 2. As far as possible, we checked our PEXRAV results with those already published on these data. For IC 4329A, Mrk 509, NGC 4151, NGC 3783, and NGC 5548, our PEXRAV fits are in good agreement with those obtained by Porola et al. (1999, 2000), Piro et al. (2000a, 2000b), De Rosa et al. (in preparation), and Nicastro et al. (2000), respectively. In the case of NGC 5548, we also checked that a better modeling of the WA (with the CLOUDY code used by Nicastro et al. 2000) does not affect the results on the continuum. We also note that, in the case of NGC 4151, we found smaller errors for the spectral index $\Gamma$ ($\Delta \Gamma \approx 0.01$) than Piro et al. (2000a), who found $\Delta \Gamma \approx 0.1$. This is simply due to the fact that the latter have computed errors using the LECS and PDS data (above 3.5 keV), whereas we have used the LECS, MECS, and PDS together (thus adding the soft excess parameters in the fitting procedure).

For the PEXRAV model, the parameters of the primary continuum determined by the fits are $\Gamma$ and $E_c$. The actual physical parameters of the Comptonizing region (also reported in Table 2) have been obtained from the spectral parameters in the following way. The temperature $kT_e$ is simply estimated as $kT_e \approx E_c/2$, keeping in mind that such an approximation roughly holds for $\tau \leq 1$. For $\tau > 1$, $kT_e \approx E_c/3$ would be more appropriate. Thus, the reported values can be considered as upper limits to the temperature.

Knowing the temperature, the optical depth can be computed from the spectral index derived from the PEXRAV fit using the following relation (Shapiro, Lightman, & Eardley 1976; Sunyaev & Titarchuk 1980; Lightman & Zdziarski 1987):

$$\Gamma - 1 \approx \left[ \frac{9}{4} + \frac{m_e c^2}{kT_e \tau (1 + \tau/3)} \right]^{1/2} - \frac{3}{2}.$$

This equation is valid for $\tau > 1$, and we have checked a posteriori that such condition is roughly matched in all cases.

4.2. The Slab Model

The fits with the AC2 yield directly and consistently the temperature $kT_e$ and optical depth $\tau$, which was our first motivation for starting this approach. The best-fit parameters are reported in Table 4. It is worth noting that another parameter enters the fitting procedure in an important way: the temperature of the soft photons, $kT_{bb}$. Its values (see Table 4) range, in most cases, between 10 and 40 eV and are relatively well constrained, with errors of the order of 5%–50%, whereas we only have data above 100 eV. For large values of $kT_{bb}$ (i.e., $kT_{bb} > 30$ eV), the high-energy tail of the blackbody shape can be detected in the low-energy part of the BeppoSAX data, and $kT_{bb}$ can then be roughly constrained. We recall that the intensity of the seed photon component with respect to the Comptonized one is also fixed by the fitted parameters (mainly $\tau$). When no tail is observed, the soft X-ray data impose at least an upper limit on $kT_{bb}$. For anisotropic geometries, the high-energy part of the Comptonization spectrum also depends on $kT_{bb}$, through the location of the anisotropy break. The fitting procedure thus has to adjust $kT_{bb}$ together with $\tau$, $kT_e$, and $R$, to reproduce the soft and hard X-ray data, resulting in a complex interdependence in the fitting procedure between the soft and hard parts of the spectra.

It is worth noting that, in the case of NGC 4151 1996L and 1996H, the best-fit values of $kT_{bb}$ are relatively large (in fact, we have only a lower limit, the AC2 working only for $kT_{bb} < 100$ eV). It is true, however, that in the case of the high state 1996H, we do not have any LECS data. Consequently, as explained above, $kT_{bb}$ is not constrained by the soft part of the spectra, and large values may be reached. However, it is surprising that in the low state 1996L we still find large $kT_{bb}$, at least 3 times larger than in 1999. A possible explanation is that, in the observation of 1996, the presence of a larger reflection component (also found with the PEXRAV fits) may hide the anisotropy break, thus diminishing the constraints on $kT_{bb}$ and allowing larger values.

4.3. Comparison between the Slab Model and PEXRAV

A purely statistical comparison between the two models is not possible, since both give acceptable values of $\chi^2$. The slab model has one more parameter and gives generally lower values of $\chi^2$, except for NGC 4151. However, we have checked, for this source, that the best-fit $\chi^2$ probability is similar for the two models. Besides, the two best fits have residuals without significant features and differences. The two models give thus an equivalent representation of the data.

4.3.1. The Temperature and Optical Depth of the Corona

For all objects, the estimated corona temperatures from PEXRAV are substantially smaller (and optical depths larger) than those inferred with an anisotropic Comptonization model. This trend is similar to the result obtained for NGC 5548 by P00. In Figure 1a we have plotted the corona temperatures obtained with AC2 versus the temperatures obtained with PEXRAV. Large differences (up to a factor of 8) are found between the two estimates. Note, however, that for IC 4329A, for which the high-energy data are comparatively better than for the rest of the sample, the two models give results that are quite close to each other.

The reason for these differences is relatively simple. Within PEXRAV-type models, the slope of the power law, determined with small errors by the LECS and MECS data, cannot change, by hypothesis, at higher energies. A cutoff
around 100 keV is then required to fit the PDS data. In Comptonization models, the LECS and MECS data determine the slope below the anisotropy break. Above this break the intrinsic spectrum is steeper and thus can fit the PDS data without an additional steepening beyond 100 keV, allowing for a larger temperature and (consequently) a smaller optical depth to keep roughly the same power-law slope.

4.3.2. The Reflection Component

The reflection normalizations obtained with AC2 cluster around 1, except for two extreme states of NGC 4151. They are, in all cases but one (ESO 141-G55), larger than those found using the simple cutoff power-law model. We show in Figure 1b the amplitude of the reflection component derived from both models. In some cases we obtain differences of factors of 4–5. Note that with the exception of NGC 4151, for all other sources the slab model yields values of R consistent with 1.

The case of NGC 4151 is peculiar, showing a large variation in R between the 1996 and 1999 observations and also an indication of a variation of R between the low and high states of the 1996 July observation. These changes are present irrespective of the model used in the spectral fitting (see also Piro et al. 2000a, 2000b). However, the slab model yields higher absolute values, also allowing for some reflection in the 1999 observation, for which PEXRAV yields \( R = 0.01 \pm 0.1 \). According to the slab model, the corona temperature is very high in the 1999 observation, which may offer a physical connection with the low value of R, as discussed in § 5.1. We can also remark that the relatively small reflection component and the hardness of the spectrum of this object may be difficult to reconcile with simple corona geometries (such as a plane or a patchy corona, for example). More complex ones (such as dynamic coronae, for example; Malzac, Beloborodov, & Poutanen 2000) may be needed. Another possibility may be that the reflecting material in NGC 4151 is highly ionized. In this case, fitting with models that do not take into account the complex ionization pattern of the reflector can severely underestimate the reflection normalization (Ballantyne, Ross, & Fabian 2000; Done & Nayakshin 2001).

As an illustration of these results, we have plotted in Figures 2a and 2b the unfolded best-fit spectra of IC 4329A and NGC 4151 (observation of 1999) obtained with PEXRAV (dashed lines) and AC2 (solid lines). We have also plotted in each case the reflection hump component to better estimate its contribution to the total spectrum. In the
case of IC 4329A, the two models give roughly the same result at high energy. For NGC 4151, however, large differences are expected between PEXRAV and AC2, with a factor of 2–3 at 300 keV and larger than 10 above 500 keV.

5. DISCUSSION

A Comptonizing corona above a passive optically thick layer (approximating an accretion disk with negligible internal heating) is a complex system, in which the soft seed photons for the Comptonization process are produced by reprocessing of the Comptonized emission in the underlying passive layer. Such a corona is “self-cooled” and, for a given geometrical configuration of the system, can only be in equilibrium if the temperature and optical depth satisfy a definite relation (Haardt & Maraschi 1991). These relations, which essentially correspond to roughly constant Compton definite relation (Haardt & Maraschi 1991). These relations, in equilibrium if the temperature and optical depth satisfy a given geometrical configuration of the system, can only be in equilibrium if the temperature and optical depth satisfy a definite relation (Haardt & Maraschi 1991). These relations, which essentially correspond to roughly constant Compton parameters $y \approx 4(kT_e/m_e c^2)[1 + 4(kT_e/m_e c^2)]\tau(1 + \tau)$, with $y \approx 0.5$ and 2 for the slab and hemisphere, respectively, have been accurately computed by Stern et al. (1995; for a review see also Svensson 1996).

In Figures 3a and 3b the values of $\tau$ versus $kT_e$, obtained for the six sources considered here using the spectral models AC2 and PEXRAV, are compared with the theoretical relations expected for a Comptonizing region in energy balance for a plane (filled rectangles, solid line) and hemispherical (filled hemispheres, dashed line) configuration, respectively.

The best-fit results obtained with AC2 (Fig. 3a) are relatively close to the theoretical expectations for the slab case, even if they tend to fall preferentially above the solid line. The data therefore indicate a Comptonization parameter larger than that for a pure slab geometry—that is, a more “photon-starved” configuration. A similar result was already derived by P00 for NGC 5548. For the latter source, best fits with a hemispherical Comptonization model were also performed. The derived coronal parameters were in fact in good agreement with the theoretical predictions for the hemisphere. However, an implausibly large value of the reflection component (of the order of 2) was required, suggesting that the real configuration is more complex than these two ideal cases. For the present sample we did not perform fits with hemispherical models.

The values of $kT_e$ and $\tau$ obtained with PEXRAV (see Fig. 3b) show the same trend as found with AC2; that is, larger values of $\tau$ for smaller values of $kT_e$. They also fall above the theoretical expectation for a slab and even above the theoretical expectation for a hemisphere (the theoretical curves of Stern et al. 1995 have been extended to large $\tau$, assuming a constant value of the Compton parameter for each curve, i.e., $y \approx 0.5$ and 2 for the slab and hemispherical configurations, respectively). Therefore, this set of parameters suggests, for each source of our sample, a configuration more “photon-starved” than a hemisphere.

An important difference with respect to the slab model is that the optical depths derived from PEXRAV fits are generally larger than 1. The corona should then be optically thick, reducing or cancelling the effects of anisotropy. Therefore also the PEXRAV model has an internal consistency. However, a corona with large optical depth may wash out discrete features from the underlying disk (e.g., lines and reflection itself; P. O. Petrucci et al., in preparation) more than would be desirable. This problem could be alleviated if the corona were “patchy” (and possibly dynamic; see § 4.3.2).

We conclude that both a hot, optically thin corona with significant anisotropic effects and a less hot, optically thick, patchy corona with negligible anisotropy are consistent with the available data.

5.1. Correlations between Physical Parameters

A correlation between the reflection normalization $R$ and the photon index $\Gamma$ has been claimed by Z99 from the study, using PEXRAV to model the primary continuum, of a large number of Ginga observations of Seyfert and Galactic black hole objects. Yet the validity of this correlation is under debate, since $R$ and $\Gamma$ are strongly correlated in the fitting procedure (Vaughan & Edelson 2000). It seems, however, more significant and less in dispute in the case of the Galactic black hole objects, where the errors on both parameters are smaller.

In Figure 4 we have plotted the reflection normalization $R$ versus the photon index $\Gamma$ we obtained with PEXRAV. In our case, we do not find a clear correlation between the two
parameters. A Spearman rank-order correlation test gives inconclusive results with $r_s \approx 0.3$. However, our sample is biased in favor of objects with hard spectra, to ensure a good detection in the PDS instrument. When the 13 objects actually observed by *BeppoSAX* are taken into account, a stronger correlation is observed (M00), in agreement with Z99.

In the case of the AC2 model, we have no simple way of characterizing the spectral shape. In addition, results are available for only six sources, and we cannot include the other Seyfert 1 galaxies observed by *BeppoSAX*. Therefore, a direct comparison with the Z99 correlation is not possible. Below, however, we examine the correlation of $R$ with the corona temperature that can be computed for the two models.

5.1.1. Relation between $R$ or $\Gamma$ and the Temperature of the Corona

Z99 interpret the correlation between $R$ and $\Gamma$ in the framework of thermal reprocessing models in which $R$ is directly proportional to the solid angle subtended by the cold matter surrounding the corona. The latter solid angle is not necessarily proportional to the soft photon flux reentering the corona, but it is likely that the larger $R$ is, the larger is the ratio of soft luminosity to hard luminosity in the corona, i.e., the smaller is the Comptonization parameter $\gamma$, resulting in softer spectra (larger $\Gamma$).

It is interesting that the *BeppoSAX* data can provide the temperatures associated with sources with different values of $R$ or $\Gamma$, which were not available from the *Ginga* data used by Z99. The result is shown in Figure 5, where we plot $R$ versus the corona temperature $E_c/2$ obtained with PEXRAV. Here again, in order to have a larger sample, we added the best-fit values obtained by M00 for the other Seyfert 1 galaxies observed with *BeppoSAX*. This plot suggests a positive correlation between the two parameters; that is, the temperature of the corona is larger for larger values of the reflection normalization. In fact a plot of $E_c/2$ versus $\Gamma$ shows that steeper spectra correspond to higher temperatures and (as a corollary) to lower optical depths (see Fig. 6).

The slab model analysis yields different trends. A plot of $R$ versus $kT_e$ for the latter model shows that sources with larger $R$ tend to have lower $kT_e$ (see Fig. 7), a behavior opposite to what is found with PEXRAV. The suggested correlation depends however strongly on the different states of NGC 4151.

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**Fig. 4.** Reflection $R$ vs. photon index $\Gamma$ from PEXRAV. The open symbols are from M00, while the filled ones are the results of this work. The filled squares represent the different observations of NGC 4151.

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**Fig. 5.** Reflection component $R$ vs. corona temperature $E_c/2$ from PEXRAV. The open symbols are from M00, while the filled ones are the results of this work. The filled squares represent the different observations of NGC 4151.

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**Fig. 6.** (a) PEXRAV corona temperature $E_c/2$ and (b) PEXRAV corona optical depth $\tau$ vs. photon index $\Gamma$. The open symbols are from M00, while the solid ones are the results of this work. The filled squares represent the different observations of NGC 4151.
To summarize, an analysis in terms of PEXRAV indicates the following correlations: larger reflection component (steeper $\Gamma$) corresponds to larger temperature (see Fig. 5), while the analysis in terms of anisotropic Comptonization yields that larger reflection corresponds to lower temperature (see Fig. 7).

The latter behavior is naturally expected in pair-free Compton-cooled coronae (see Fig 3a), since the transition to lower Compton parameter (i.e., higher $l_h/l_s$, as suggested by a larger $R$) implies a decrease in the temperature for constant optical depth, as (relatively well) verified by our sources.

The behavior indicated by PEXRAV could instead be understood better in the case of a pair-dominated corona in pair equilibrium. In such a case, for constant hard compactness, the larger the ratio $l_h/l_s$, the larger the temperature of the corona. This behavior is simply imposed by the pair equilibrium. Indeed, an increase of the cooling corresponds to a decrease of the number of particles in the hard tail of the thermal particle distribution. To reach a new equilibrium, the temperature must increase (Zdziarski 1985; Svensson 1982; Ghisellini & Haardt 1994; Coppi 1999).

A possible limitation of the “pair-dominated” interpretation comes from the high values of the compactness $l_h$ required by the physical parameters determined with PEXRAV. We show in Figure 8 the $\tau$-$T_e$ relations expected for a pair-dominated corona, for different values of $l_h$ but varying the ratio $l_h/l_s$. We have also included the observations of M00. The data require values of $l_h$ in the range 100–1000. Given the (unabsorbed) luminosity of the sources of our sample ($L_{0.1–200\,\text{keV}}$ of the order of $10^{44}$ ergs cm$^{-2}$ s$^{-1}$), this implies black hole mass upper limits of the order of $10^7 M_\odot$ (for $l_h = 100$). This is relatively smaller than (but roughly consistent with) black hole mass estimations obtained from reverberation mapping or resolved kinematics methods for most of the objects of our sample (see Gebhardt et al. 2000; Nelson 2000, and references therein). The worse case is that of NGC 4151, where the PEXRAV best-fit values of $kT_e$ and $\tau$ require very large hard compactness (larger than 1000), implying a black hole mass of $\sim 10^5 M_\odot$ (reverberation mapping methods estimate a black hole mass of $\sim 10^7 M_\odot$; Clavel et al. 1987; Ulrich & Horne 1996). In this case, however, the complexity of the soft part of the spectrum may lead to an incorrect modeling of the continuum. We therefore conclude that the pair-dominated corona interpretation is also still valid for this object. Other observations (with better constraints on the compactness and the physical parameter of the corona) are clearly needed to confirm or disprove these results.

6. CONCLUSION

The aim of this paper was to test anisotropic Comptonization models over the high-S/N BeppoSAX observations of a sample of six Seyfert 1 galaxies (seven observations). We use two types of model: a detailed Comptonization code in slab geometry, which carefully treats the anisotropy effects in Compton processes, and a simple cutoff power-law plus reflection model (PEXRAV model of XSPEC). The latter is generally used as a zeroth-order approximation to Comptonization spectra. If this is a relatively good approximation for isotropic geometry, it fails to reproduce the real shape of Comptonization spectra in anisotropic ones (such as a plane, hemispherical, or spherical hot region above a flat disk). In this case, because of the deficiency of the first-order scattering component toward the observer, it better resembles a broken power law with convex curvature. This leads to strong differences between the best-fit parameter values obtained with these two models. The main results of this work are as follows:

1. The data are well fitted by both models, and there is no statistical evidence that one model is better than the other. Both models give results in agreement with an X-ray source geometry more “photon starved” than the slab case.

2. Our best fits with Comptonization models in slab geometry give a temperature that is generally much larger and an optical depth that is much smaller than derived from the power law + cutoff fits, using standard Comptonization formulae. The estimate of the reflection normalization is also larger with the slab corona model.

The two models also lead to different relationships between physical parameters. For instance, PEXRAV indicates a correlation between the reflection normalization and the corona temperature, whereas the slab corona model suggests an anticorrelation. This has major consequences.
for the physical interpretation of the data. Thus, the PEXRAV results suggest that the hot corona may be pair-dominated, whereas the slab corona model is in better agreement with a low pair density solution.

These results should have observational consequences. First, the large differences in the fitted temperatures lead to widely different predictions as to the fluxes emitted at higher energies, above the PDS range. This underlines the need for better soft γ-ray observations, such as those possibly provided by the International Gamma-Ray Astrophysical Laboratory (INTEGRAL), in order to directly confirm or disprove the temperatures inferred with anisotropic Comptonization models.

On the other hand, the large values of τ predicted by PEXRAV would spread out the reflection hump in the entire X-ray range, preventing any detection of this component. The fact that we obtain not negligible values of R with PEXRAV may, however, be reconciled with the large values of τ if the corona is “patchy.” Indeed, in this case, reflection could come from the uncovered part of the cold, reflecting material. Part of the reflection could also come from the torus. The variability of the reflection component may allow us to differentiate these two possibilities. Large values of τ would also modify the profile of the Fe line component produced in the disk, leading to an attenuation and broadening of the line. Forthcoming observations with Chandra and XMM-Newton are expected to bring substantial progress on this issue.

P. O. P. acknowledges a grant from the European Commission under contract number ERBFMRX-CT98-0195 (TMR network “Accretion onto black holes, compact stars and protostars”). This work was partially supported by the Italian MURST through the grant COFIN98-02-15-41 (J. M.) and by the Agenzia Spaziale Italiana (ASI) trough the grant ASI-ARS-99-74 (L. M., F. H.).

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V (San Francisco: ASP), 17

Bailyn, D. N., Ross, R. R., & Fabian, A. C. 2000, MNRAS, in press (astro-ph/0010204)

Boella, G., et al. 1997, A&AS, 122, 327

Capri, M., Mihara, T., Matsuoka, M., Hayashida, K., Weaver, K. A., & Ohtani, C. 1996, ApJ, 458, 149

Chavel, J., et al. 1987, ApJ, 321, 251

Coppi, P. 1999, in ASP Conf. Ser. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 375

Done, C., & Nayakshin, S. 2001, ApJ, 546, 419

Elvis, M., Briel, U. G., & Henry, J. P. 1983, ApJ, 268, 105

Evans, I. N., Tsvetanov, Z., Kriss, G. A., Ford, H. C., Cagano†, S., & Elvis, M., Wilkes, B. J., & Lockman, F. J. 1989, AJ, 97, 777

Elvis, M., & Briel, U. G. 1993, ApJ, 407, L61

Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 273, 837

Lightman, A. P., & Zdziarski, A. A. 1987, ApJ, 319, 643

Ballantyne, D. R., Ross, R. R., & Fabian, A. C. 2000, MNRAS, in press

Matsuoka, M., Piro, L., Yamauchi, M., & Murakami, T. 1990, ApJ, 361, 440

Morse, J. A., Wilson, A. S., Elvis, M., & Weaver, K. A. 1995, ApJ, 439, 121

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P. O. P. acknowledges a grant from the European Commission under contract number ERBFMRX-CT98-0195 (TMR network “Accretion onto black holes, compact stars and protostars”). This work was partially supported by the Italian MURST through the grant COFIN98-02-15-41 (J. M.) and by the Agenzia Spaziale Italiana (ASI) trough the grant ASI-ARS-99-74 (L. M., F. H.).