X-ray and soft $\gamma$-ray spectra of Broad-Line Radio Galaxies

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ABSTRACT

We study X-ray and soft $\gamma$-ray spectral properties of nearby Broad-Line Radio Galaxies (BLRGs) using data from Ginga, ASCA, OSSE and EXOSAT. The X-ray spectra are well fitted by an intrinsic power-law continuum with an energy index of $\alpha \sim 0.7$, moderately absorbed by a cold medium. In addition, the Ginga spectra show fluorescent Fe Kα lines with an average equivalent width of $\sim 100$ eV, and, in some cases, Compton reflection humps. However, the latter components are significantly weaker than both those seen in radio-quiet Seyferts and those expected if the Fe Kα lines were due to reflection. We find that this weakness of reflection cannot be explained by dilution by another continuum component, e.g., from a jet. Some ASCA and EXOSAT spectra show soft X-ray excesses below $\sim 3$ keV. When that component is taken into account, the Fe Kα lines in the ASCA data are found to be unresolved in most cases, and to have equivalent widths $< \sim 200$ eV, consistent with the Ginga data.

Multiple observations of 3C 390.3 and 3C 382 show the Fe Kα line approximately constant in flux but accompanied by strong continuum variations. This indicates the bulk of the line is formed by matter at a distance much larger than an accretion-disk scale, consistent with the ASCA line width measurements. The column density of the matter required to account for the observed line fluxes is $N_H \gtrsim 10^{23}$ cm$^{-2}$. Such a medium is in the line-of-sight in 3C 445 but it has to be out of it in other objects, in which the observed $N_H$ are substantially lower. Thus, a cold medium with that $N_H$ and covering a large solid angle is common in BLRGs but in most object it is out of the line-of-sight, consistent with the unified AGN model.

The spectra of BLRGs break and become softer above $\sim 100$ keV, as shown by a simultaneous ASCA/OSSE observation of 3C 120 and by the OSSE spectra being on average much softer than the X-ray spectra. Finally, we find the X-ray and $\gamma$-ray spectral properties of Cen A, a bright narrow-line radio galaxy – $\alpha \simeq 0.8$, no or weak Compton reflection, $N_H \gtrsim 10^{23}$ cm$^{-2}$ (which is consistent with the Fe Kα line flux), and a high-energy break at $\sim 100$ keV – consistent with it being intrinsically very similar to BLRGs studied here, again in agreement with the unified model.

Key words: galaxies: active – galaxies: individual (3C 111, 3C 120, 3C 382, 3C 390.3, 3C 445, Cen A) – galaxies: Seyfert – gamma-rays: observations – line: profiles – X-rays: galaxies.

1 INTRODUCTION

The 2–20 keV X-ray spectra of Seyfert 1s have been studied using the Ginga data by Nandra & Pounds (1994, hereafter NP94). Those spectra have been found not to be simple power laws, but, instead, to show the presence of a characteristic spectral upturn above $\sim 10$ keV (see also Pounds et al. 1990), satisfactorily explained by Compton reflection from cold matter, presumably an accretion disk (Lightman & White 1988). However, NP94 have not distinguished in their study radio-quiet Seyferts from radio-loud ones, i.e, nearby broad-line radio galaxies (hereafter abbreviated as
BLRGs). On the other hand, Zdziarski et al. (1995, hereafter Z95) have found that two BLRGs observed by both Ginga and CGRO/Oriented Scintillation Spectroscopy Experiment (OSSE), 3C 111 and 3C 390.3, have the average spectrum with weak or no Compton reflection. That average spectrum is similar to the intrinsic spectrum of the nearby narrow-line radio galaxy Cen A, which also does not show Compton reflection (Miyazaki et al. 1996; Warwick, Griffiths & Smith 1998).

Here we study X-ray and soft $\gamma$-ray (hereafter abbreviated as X-\gamma) spectra of BLRGs observed by Ginga, ASCA, OSSE and EXOSAT. These radio-loud sources can be classified as Seyfert 1s using optical and UV lines and are listed as such by NP94. The morphology of most of the objects is consistent with elliptical (see Section 4). Our sample contains 5 BLRGs, of which 4 were observed by Ginga, 5 by ASCA, 3 by OSSE, and 5 by EXOSAT. Table 1 contains basic information on these objects. We selected the sources having radio to optical flux ratio $F(5 \text{ GHz})/F(B \text{ optical}) \gg 10$ (Kellermann et al. 1989).

In Section 2 we describe the data used, and in Section 8 we present models used for the subsequent spectral fits. The results on individual objects are presented in Section 3. We specifically address the issues of the presence of the Compton reflection component and the strength and width of the fluorescence Fe Kα line. In Section 4, we discuss the average sample properties, the presence of breaks in soft $\gamma$-rays, and differences in X-ray spectral properties between BLRGs and radio-quiet Seyfert 1s. In Section 5, we consider the X-\gamma spectra of the narrow-line radio galaxy Cen A, and compare them to those of our sample of BLRGs. In Section 6, we interpret our results, and summarize the main conclusions in Section 7.

2 THE DATA

For our study, we have selected BLRGs detected by either Ginga, ASCA, or OSSE. In addition, we consider observations of those objects by EXOSAT.

A total of 5 radio-loud Seyfert 1s were observed by Ginga LAC (the numbers of individual observations are given in brackets): 3C 98 [1], 3C 111 [1], 3C 382 [3], 3C 390.3 [2], and 3C 445 [1]. A rigorous data selection policy was adopted in order to exclude periods of high or unstable background (see, e.g., Smith & Done 1996). 3C 98 has not been detected and thus it is not included in our analysis. Table 1 contains the observation log for Ginga. The observations of 3C 111, 3C 382 and of the 1988 observation of 3C 390.3 are included in the sample of NP94, and of 3C382, 3C390.3, and 3C 445 in the sample of Lawson & Turner (1997).

The background was estimated using one of the two methods given by Hayashida et al. (1989) (see also Williams et al. 1992). The local method uses off-source observations taken within two days of (or at the same orbital phase as) the on-source observation to estimate the background level at the time of the observation, while the universal method uses all the off-source observations taken within a contemporary four month period to model systematic trends in the particle background levels, and hence to estimate the background level at the time of the source observation. It is found that the universal method gave poor results for one observation of 3C 390.3 and all observations of 3C 382. For the remaining observations we used the results obtained from the universal method as it minimises the fluctuations in the cosmic X-ray background (Hayashida et al. 1989; Williams et al. 1992). For 3C 382 and 3C 445, the weakest of the sample, we have also added and subtracted a power law with $\alpha = 0.8$ with the 1-keV normalization of $5 \times 10^{-4} \text{ cm}^{-2} \text{s}^{-1}$ (representing background fluctuations) to the data. The effect on the spectral slope below 10 keV was small, $\pm 0.05$, and completely negligible above 10 keV. Thus, we ignore this effect in fitting the data. Finally, due to the low Galactic latitude of 3C 111, the Ginga observation is possibly contaminated by the soft diffuse X-ray emission from our galaxy. To overcome this, we subtracted the best estimate of the local soft X-ray emission (derived from a nearby off-source observation) from the source data.

Data were then extracted from both the top-layer and mid-layer of the LAC, as the mid-layer has more effective area above $\sim 10$ keV (although we ignore the mid-layer data below 10 keV as these are subject to greater uncertainties in background estimation). Contamination from fluorescence by silver atoms in the LAC collimator complicates the spectral analysis around $\sim 22$ keV; for this reason, our analysis is restricted to the $\sim 1.7–18$ keV energy range. Prior to spectral fitting, the data were corrected for the collimator response and a 0.5 per cent systematic error was added to each pha channel, to account for uncertainties in the detector response.

ASCA satellite consists of four co-aligned X-ray telescopes, and it covers a bandpass roughly from 0.4 to 10 keV (see Tanaka, Inoue & Holt 1994). The focal planes of two of the four telescopes have Gas Scintillation Imagers (GISs), while the remaining two have X-ray sensitive CCD cameras (Solid-state Imaging Spectrometers, or SISs), each consisting of four CCD detectors (chips). The observations of 3C 111 [1], 3C 120 [1], 3C 390.3 [3] and 3C 445 [1] were performed in a standard spectroscopy configuration with the source focussed on chip 1 in the SIS0 and on chip 3 in the SIS1. The observation of 3C 382 was performed with the source focussed on chip 2 in the SIS0 and on chip 0 in the SIS1 (a somewhat non-standard configuration). The log of the ASCA observations is given in Table 3.

The data were extracted from the HEASARC archives, and reduced using standard ASCA data reduction procedures. We used the ASCA rev. 2 processing, extracting manually the event files, but in the process of doing so, we used the standard screening criteria. In all cases, the SIS data presented here were analyzed in the highest spectral resolution “faint” mode, to assure that there would be no additional gain offset from the potential contamination by the scattered sunlight. For 3 objects, this results in a slightly lower effective observation time and thus slightly lower statistics than in the “bright” mode. However, there was no discernible difference between the results of the “faint” and “bright” mode spectral fits, as discussed in Section 4 below. On the other hand, the use of the “faint” mode for 3C 111 and 3C 382 resulted in only about 40 per cent of SIS0 data and 50 per cent of all SIS data, respectively, as compared to the “bright” mode. Therefore, in addition to the “faint” mode, we also performed the spectral fits to the data analyzed in...
Table 1. The sample of BLRGs. The coordinates, redshifts, and Galactic column densities, $N_{\text{HI}, G}$ (in units of $10^{21}$ cm$^{-2}$) are from Malaguti, Bassani & Caroli (1994). The NED database was used for the 5-GHz fluxes, $F_{5\text{GHz}}$. The extinction-corrected $B$ magnitudes were taken from Smith & Heckman (1989) except for 3C 111, where we used the V magnitude from Brinkmann et al. (1995) and adopted $B - V = 1.7$ from the AGN catalog of Véron-Cetty & Véron (1993).

| Object | R.A. | Dec. | z | $N_{\text{HI}, G}$ | $F_{5\text{GHz}}/F_{B}$ |
|--------|------|------|---|-------------------|------------------------|
| 3C 111 | $04^h15^m06^s.4$ | $+37^\circ54'16''$ | 0.049 | 3.26 | 12400 |
| 3C 120 | $04^h30^m31^s.6$ | $+05^\circ15'00''$ | 0.033 | 1.23 | 500 |
| 3C 382 | $18^h33^m12^s.0$ | $+32^\circ39'18''$ | 0.058 | 0.79 | 400 |
| 3C 390.3 | $18^h45^m37^s.7$ | $+79^\circ43'06''$ | 0.056 | 0.41 | 4300 |
| 3C 445 | $22^h21^m14^s.7$ | $-02^\circ21'25''$ | 0.056 | 0.50 | 1100 |

Table 2. The observation log for Ginga. The count rate is for the top layer of the LAC in the 1.7–10 keV energy range. The uncertainties here and in Table 4 below correspond to 1-sigma confidence intervals.

| Object | Start date | Start time | End date | End time | Exposure [s] | Count rate [s$^{-1}$] |
|--------|------------|------------|----------|----------|--------------|-----------------------|
| 3C 111 | 1989-Feb-04 | 08:30:00 | 1989-Feb-05 | 11:00:00 | 18944 s | 12.42 ± 0.06 |
| 3C 382 | 1989-Jul-20 | 08:20:00 | 1989-Jul-21 | 06:35:00 | 15488 s | 5.51 ± 0.08 |
| 3C 390.3 | 1991-Nov-12 | 02:00:00 | 1991-Nov-14 | 03:00:00 | 46720 s | 17.40 ± 0.06 |
| 3C 445 | 1988-Nov-02 | 06:00:00 | 1988-Nov-03 | 07:00:00 | 27648 s | 9.61 ± 0.06 |

Table 3. The observation log for ASCA. The count rates for SIS and GIS are given in the 0.55–10 keV energy band. The statistical errors of the count rates are $< 0.01$ s$^{-1}$, except for 3C 445, where the error is $< 0.002$ s$^{-1}$.

| Object | Date | Start time | Exposure [s] | Count rate [s$^{-1}$] |
|--------|------|------------|--------------|-----------------------|
| 3C 111 | 1996-Feb-13 | 12:35:19 | 10200 s | 0.62 SIS0 |
| 3C 120 | 1994-Feb-17 | 15:42:24 | 43500 s | 1.67 SIS1 |
| 3C 382 | 1994-Apr-18 | 09:24:22 | 18300 s | 1.50 GIS2 |
| 3C 390.3 | 1993-Nov-16 | 22:40:14 | 28800 s | 0.49 GIS3 |
| 3C 445 | 1995-Jun-01 | 11:43:49 | 33600 s | 0.57 GIS0 |

Table 4. The observation log for OSSE. VP stands for the Viewing Period of CGRO. The net exposure time and the count rates are normalized to a single OSSE detector. The count rates and the photon fluxes (in units of $10^{-4}$ s$^{-1}$ cm$^{-2}$) are given for the 50–150 keV band, and the energy spectral index, $\alpha$, for the 50–500 keV band.

| Object | VP | Start date | End date | Exposure [s] | Count rate [10$^{-2}$ s$^{-1}$] | Photon flux | $\alpha$ |
|--------|----|------------|----------|--------------|-----------------------------|-------------|--------|
| 3C 111 | 4  | 1991-Jun-28 | 1991-Jul-12 | 440,233 s | 15.04 ± 2.52 | 3.20 ± 0.60 | 1.04 ± 0.34 |
| 29 | 1992-May-14 | 1992-Jun-04 | 184,973 s | 5.64 ± 3.67 | 1.86 ± 1.12 | −0.21 ± 1.06 |
| 30 | 1992-Jun-04 | 1992-Jun-11 | 154,046 s | < 9.22 | < 2.21 |
| 33 | 1992-Jul-02 | 1992-Jul-16 | 288,222 s | 19.75 ± 3.30 | 4.60 ± 0.78 | 2.02 ± 0.50 |
| 220 | 1993-May-08 | 1993-May-13 | 94,259 s | 17.68 ± 5.00 | 3.91 ± 1.16 | 1.25 ± 0.81 |
| 224 | 1993-Jun-04 | 1993-Jun-14 | 459,622 s | 15.12 ± 2.23 | 3.41 ± 0.52 | 1.20 ± 0.34 |
| 317 | 1994-Feb-17 | 1994-Mar-01 | 208,365 s | 8.16 ± 4.29 | 1.63 ± 1.01 | 0.55 ± 0.83 |
| 320 | 1994-Mar-08 | 1994-Mar-15 | 201,880 s | 8.11 ± 4.53 | 2.05 ± 1.07 | 4.10 ± 2.28 |
| 617.7 | 1997-Mar-18 | 1997-Apr-01 | 669,576 s | 9.01 ± 2.72 | 1.96 ± 0.65 |
| 617.7 | 1997-Apr-07 | 1997-Apr-09 | 109,300 s | 13.77 ± 7.38 | 3.28 ± 1.76 |
| 3C 309.3 | 12 | 1991-Oct-18 | 1991-Oct-31 | 375,313 s | 18.07 ± 2.92 | 4.01 ± 0.69 | 1.38 ± 0.43 |
| 29 | 1992-May-15 | 1992-Jun-04 | 390,664 s | 11.55 ± 2.52 | 2.58 ± 0.60 | 1.19 ± 0.45 |
| 209 | 1993-Feb-10 | 1993-Feb-22 | 330,724 s | 5.69 ± 3.13 | 1.26 ± 0.74 | 1.19 ± 1.08 |
| Sum | 1991-Oct-18 | 1993-Feb-22 | 1,096,700 s | 12.01 ± 1.64 | 2.54 ± 0.40 | 1.36 ± 0.32 |
| Sum | 1991-Jun-28 | 1997-Apr-09 | 4,079,887 s | 11.34 ± 0.91 | 2.57 ± 0.22 | 1.15 ± 0.16 |

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the “bright” mode for those 2 objects, see Sections 4.2 and 4.4.

The resulting spectra were then binned to assure that there are $\geq 20$ counts per bin. In addition, for the observation of 3C 120, due to an on-board electronics malfunction in the GIS3 – where the two least significant bits of the analog-to-digital converter in the Pulse Height Discriminator circuit were stuck in a fixed pattern – all data for GIS3 needed to be binned with at least 8 channels to a bin. In all cases, the source photons were extracted using circular regions, with radii of 3′ for the SISs, and 6′ for the GISs, while the background, to be subtracted prior to the spectral fits from the source counts to get the net spectra, was extracted from suitable source-free regions of a size comparable or greater than the source regions.

For the GIS data, in our spectral fitting, we used the standard GIS response matrices (v4.0). For the SIS data, we used the SIS response matrix generator (sisrmg), as appropriate to every observation and detector, v1.1, April 1997. For both SIS and GIS data, we used the telescope effective regions (via the use of ascaarf v2.72, March 1997). To account for the residual errors in the relative cross-calibration of the four telescopes, we fit the same model to the four data sets with each normalization as a free parameter. For plotting purpose only, we further rebin, renormalize and add the data from all 4 detectors using the normalization of SIS0.

That normalization is also used for comparison with results of other instruments. We note that the relative normalization differences in our data with respect to SIS0 are $< 13$ per cent except for the 3C382 observation (which used the non-standard observation configuration as described above) where the differences are $< 26$ per cent.

Most of the OSSE data used here have been briefly reported in Johnson et al. (1997). The analysis of 3C 111 [2], 3C 120 [9] and 3C 390.3 [3] takes into account a systematic error correction to the spectra computed from the uncertainties in calibration and response of the detectors using both in-orbit and pre-launch data. The systematic errors correspond to $\sim 3$ per cent uncertainty in effective area at 50 keV, decreasing to $\sim 0.3$ per cent at 150 keV and above. We use the OSSE response matrix as revised in 1995, which results in the 50–60 keV fluxes about 20 per cent higher than in the original response (used, e.g., in Z95). Observation log for OSSE is given in Table 4.

We supplement the above data set by selected data from EXOSAT. We use EXOSAT ME spectra from the HEASARC archive with the quality flag 3 or higher, which indicates observations with reliable background subtraction (note that this criterion removes 3C 111 from the sample). The objects are 3C 120 [14], 3C 382 [24], 3C 390.3 [4], and 3C 445 [1] (some of those observations are reported in Turner & Pounds 1989). The usable EXOSAT energy range is from 1.2 keV to 8 keV in most cases as the spectra above 8 keV suffer from relatively inaccurate background subtraction. The individual spectra include a 1 per cent systematic error. Since the individual spectra are of rather low statistical significance, we use co-added spectra of each of the first 3 objects with the weights corresponding to the length of time of each observation. Both the counts and the response matrices for each observation were added using the ADDSPEC function of the FTOOLS data processing package. Time intervals covered by the observations are 1983 March–1986 February, 1983 September–1985 September, 1985 February–1986 March, and 1984 May for 3C 120, 3C 382, 3C 390.3 and 3C 445, respectively. We note that the Fe K line energies in the EXOSAT data appear at energies significantly lower than those obtained with Ginga and ASCA, which appears to be due to a calibration problem.

3 SPECTRAL MODELS

We use xspec (Arnaud 1996) v9 and 10 for spectral fitting. The parameter uncertainties in Tables below correspond to 90 per cent confidence for a single parameter, i.e., $\Delta \chi^2 = 2.7$. On the other hand, the plotted error bars are 1-$\sigma$, the upper limits, 2-$\sigma$, and the spectral data are rebinned for clarity of display.

Fitted intrinsic spectra are absorbed by intervening matter with the column density that consists of both the Galactic component, $N_{H,G}$ (see Table [I]), and the column density intrinsic to the source, $N_H$ (note that $N_H$ does not include $N_{H,G}$). Both the intrinsic spectra and absorption by $N_H$ are evaluated at the source redshift, $z$. The absorption is in neutral matter with the abundances of Anders & Ebihara (1982) and the opacities of Morrison & McCammon (1983), as implemented in the zvabs model of XSPEC.

We model the underlying continuum as a power law with an energy spectral index, $\alpha$, multiplied by an exponential with an e-folding energy, $E_c$. When fitting the X-ray data only, we assume $E_c = 400$ keV, consistent with results of Z95. This, however, has a negligible effect on the resulting parameters. On the other hand, $E_c$ is a free parameter in fits to combined X$\gamma$ data.

We also allow for the presence of a Compton-reflection spectral component (Lightman & White 1988). Compton reflection arises when the underlying component irradiates cold matter in the vicinity of the nucleus, e.g., an accretion disk or a torus. We use Green’s functions for angle-dependent reflection of isotropic incident radiation of Magdziar & Zdziarski (1995), and assume the viewing angle of 30° (corresponding to an orientation close to face-on, as expected in type-1 AGNs, Antonucci 1993, see also Eracleous, Halpern & Livio 1996 for 3C 390.3). The relative amount of reflection is measured by the solid angle subtended by the reflector, $\Omega$ ($\Omega = 2\pi$ corresponds to reflection from an infinite slab). The opacities of reflector are the same as for the absorber. However, we consider some models with the Fe abundance with respect to that of Anders & Ebihara (1982), $A_{Fe}$, being $> 1$. In some cases, we also allow the reflecting medium to be ionized, in which case we use the model of Done et al. (1992) modified as in Gondek et al. (1996). We assume the reflector temperature of 10$^5$ K (Krolik & Kallman 1984). The ionization parameter is defined as $\xi \equiv L_{ion}/nr^2$, where $L_{ion}$ is the luminosity in an incident power-law continuum in the 5 eV–20 keV range, $n$ is the density, and $r$ the distance between the source of radiation and the reflector. The neutral and ionized reflection is implemented in the XSPEC models pexrav and pexriv, respectively.

Both reflection and absorption of the continuum are accompanied by emission of fluorescent lines, the most prominent of those is the Fe K\alpha line (at 6.4 keV in the case of neutral Fe), which we model as a Gaussian at an energy,
4 RESULTS OF SPECTRAL FITS

4.1 3C 445

3C 445 is a powerful FR II BLRG with a typical lobe-dominated radio morphology and an elliptical appearance in the optical band (Smith & Heckman 1989). The source lies ~0.5' from the cluster A 2440, which thus contaminates the spectrum of 3C 445 (Pounds 1990) from Ginga (which has the field of view of 1' × 2'). The cluster emission has been modelled by Pounds (1990) as thermal bremsstrahlung at $kT = 3$ keV. We note that this component would also include any soft X-ray excess of the AGN itself. We fit the updated Ginga data (see Section 2) by the sum of of that component, an absorbed power law with Compton reflection and an Fe K line, and obtain the parameters given in the Table 5. They are consistent with those of Pounds (1990) within the statistical uncertainties, although Pounds (1990) obtains a somewhat softer spectral index, $\alpha = 0.68^{+0.20}_{-0.18}$, which is apparently due to differences in data processing. Similarly to Pounds (1990), we find the X-ray source is strongly obscured. The Ginga spectrum is shown in Figure 1a.

We see in Table 5 that the Ginga data do not require the presence of a Compton reflection component, and $\Omega/2\pi \lesssim 0.2$. (The top-layer Ginga data alone are consistent with this result, but yield a weaker constraint of $\Omega/2\pi = 0.20^{+0.00}_{-0.20}$.) On the other hand, there is a strong Fe K line in the spectrum (modeled here as absorbed by $N_{\text{H},G}$ only). The line originates in both the cluster and the AGN.

The cluster emits a thermal emission line at the rest-frame energy of 6.7 keV with $W_{\text{K}} \simeq 500$ eV with respect to the bremsstrahlung spectrum (Pounds 1990 and references therein). At $z = 0.094$ of A 2440 (Struble & Rood 1987), the observed centroid energy of the cluster line is 6.12 keV and cannot be resolved by Ginga from the fluorescent line from 3C 445 redshifted from 6.4 keV to 6.05 keV. Thus, we model both line components as a single Gaussian. The line flux, $I_{\text{K}}$, in Table 5 corresponds to both components, whereas the stated $W_{\text{K}}$ corresponds to the AGN component only with respect to the absorbed power-law continuum.

The ASCA data, on the other hand, are basically free from contamination from the cluster. In our modeling of the continuum, we use a model with 3 power-law components each absorbed by a different column density, which was shown to be the simplest model accounting for the shape of the spectrum from ASCA in an early analysis of the data by Yamashita & Inoue (1996). The fit parameters are given in Table 5, and the spectrum is shown in Figure 1b. We see that the spectrum of 3C 445 contains a substantial soft X-ray excess component, modeled here as the third power-law component with $N_{\text{H}}$ consistent with null (Table 5). That component can be interpreted as being due to the product of uniform absorption with $N_{\text{H},2}$ and partial covering by $(N_{\text{H},1} - N_{\text{H},2})$ with a covering fraction of $A_1/(A_1 + A_2)$.

The obtained spectral index and the line parameters are similar to those derived above from the Ginga data. In particular, the obtained line equivalent width is almost the same as $W_{\text{K}}$ estimated above after subtracting the cluster component in the Ginga data. We also find the Fe K line...
is narrow, $\sigma_{\text{Fe}} < 0.18$ keV. The $\sigma_{\text{Fe}}$-$E_{\text{Fe}}$ confidence contours are presented in Figure 2, and the line profile is shown in Figure 3. Note that the presence of a soft excess component in the spectrum of 3C 445 shown by ASCA implies that a (minor) part of the soft excess (modeled as bremsstrahlung) in the Ginga and EXOSAT data actually comes from the AGN itself.

Our ASCA results can be compared with a recent independent analysis of the data by Sambruna et al. (1998). Their best-fit model has the identical form to ours. However, they obtain a harder power law than that obtained by us, with $\alpha = 0.25^{+0.29}_{-0.27}$, and a broader and stronger Fe K line, with $\sigma_{\text{Fe}} = 0.16^{+0.16}_{-0.13}$ keV (in the source frame), and $I_{\text{Fe}} = (5.0^{+4.0}_{-2.9}) \times 10^{-5}$ s$^{-1}$ cm$^{-2}$. These differences can be explained by their use of an earlier (of 1994) version of the ASCA software than that used by us (of 1997). Furthermore, the reduced $\chi^2$ of their best-fit model is statistically significantly larger than ours (1.05 vs. 1.02). Thus, we conclude that the ASCA data are fully compatible with the Fe K line being narrow, as obtained by us.

The $W_{\text{Fe}} \sim 150$ eV obtained by us for both Ginga and ASCA data is consistent with emission of a shell of cold matter with $N_{\text{H}} \sim (2-5) \times 10^{21}$ cm$^{-2}$ and the cosmic Fe abundance irradiated isotropically from the center (Makishima 1986, hereafter MS86; Awaki et al. 1991). We thus conclude that the most likely origin of the Fe K emission in 3C 445 is fluorescence in the observed absorber, which, we infer, covers a large solid angle around the nucleus. This interpretation is consistent with the narrowness of the line derived from the ASCA data. The presence of an optically-thick disk irradiated isotropically by the X-ray source appears to be ruled out as the solid angle of any reflector is constrained to $\ll 2\pi$.

Figure 1c shows a comparison of 3C 445 spectra from different instruments. Here, we also show the spectrum from EXOSAT, fitted in the 1–15 keV range in the same way as the Ginga data except that the Fe K line is not included in the model due to the limited statistical quality of the former data. The cluster contribution to the EXOSAT data is about a quarter of that in the Ginga data, which is fully consistent with the field of view of EXOSAT ($45' \times 45'$) being smaller than that of Ginga. On the other hand, the spectra of the AGN itself from Ginga and EXOSAT are consistent with being the same. However, the ASCA spectrum lies significantly below the other two spectra even at hard X-ray energies, where the cluster contribution is negligible. This indicates the presence of X-ray variability in 3C 445, caused by either variability of the power-law component or variable absorption.

### 4.2 3C 111

3C 111 is a luminous FR II radio galaxy with bright core, a one-sided jet on milli-arcsecond scale (Linfield & Perley 1984), a highly asymmetric double radio structure, and reported superluminal motion ($\gtrsim 10c$, Preuss, Aléf & Kellermann 1988). The optical image shows no structure (Colina & Pérez-Fournon 1990) and thus exact classification is not

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**Table 5.** Results of fits to the 3C 445 data from Ginga, ASCA and EXOSAT. The Ginga and EXOSAT data contain a cluster contribution at low energies, which is modeled by a 3-keV bremsstrahlung photon spectrum, $A_2 \exp(-E/kT)$ times the Gaunt factor.

| Year         | $A_i$   | $N_{\text{H,i}}$ | $\alpha$ | $\Omega/2\pi$ | $E_{\text{Fe}}$ | $\sigma_{\text{Fe}}$ | $I_{\text{Fe}}$ | $W_{\text{Fe}}$ | $\chi^2$/dof($\chi^2$) |
|--------------|---------|------------------|----------|---------------|----------------|----------------------|----------------|--------------|------------------------|
| Ginga 1988 Nov | $3.2^{+1.7}_{-0.6}$, $4.3^{+0.2}_{-0.2}$ | $150^{+30}_{-30}$, 0f | $0.45^{+0.14}_{-0.10}$ | $0^{+0.02}_{-0.02}$ | $6.37^{+0.22}_{-0.19}$ | 0.1f | $4.7^{+1.7}_{-2.1}$ | 150 | 35.3/36(0.98) |
| Ginga 1995 Jun | $1.9^{+2.6}_{-1.2}$, $0.87^{+0.54}_{-0.39}$, $0.15^{+0.02}_{-0.02}$ | $580^{+370}_{-230}$, $78^{+21}_{-20}$, $0^{+0.6}_{-0.6}$ | $0.39^{+0.28}_{-0.29}$ | 0f | $6.44^{+0.07}_{-0.07}$ | $0^{+0.18}_{-0.15}$ | $1.8^{+0.6}_{-0.7}$ | 140 | 429/421(1.02) |
| EXOSAT 1984 May | $2.5^{+3.0}_{-1.4}$, $0.62^{+0.87}_{-0.62}$ | $80^{+100}_{-50}$, 0f | $0.33^{+0.07}_{-0.40}$ | 0f | – | – | – | – | 35.8/43(0.83) |
possible, but the properties of the host galaxy are consistent with elliptical morphology.

The spectrum of 3C 111 from Ginga was included in the sample of NP94. The parameters of our fits to the Ginga observation are reported in Table 6 and the spectrum is shown in Figure 4. The Fe K line energy, \(\sim 6.7\) keV (although lower than 7.4 keV found by NP94), suggests emission by strongly ionized iron. The remaining fit parameters are similar to those of NP94, in particular there is little evidence for reflection. (The top-layer Ginga data alone are also consistent with the absence or weakness of reflection, yielding \(\Omega/2\pi = 0^{+0.16}_{-0.10}\).) On the other hand, the best-fit value of \(W_{\text{Fe}} \approx 80\) eV appears too large for the Fe K line to be due to reflection. However, the uncertainties on the fitted parameters are such that the origin of the Fe K line from Compton reflection is still possible. In particular, we have

![Graph](image-url)
fitted a model in which the line equivalent width was tied to the reflected component. Theoretical estimates of $W_{\text{Fe}}$ with respect to the Compton-reflected component are relatively uncertain and vary from $\sim 0.7$ keV to $\sim 1.5$ keV for $\Omega = 2\pi$, $\alpha = 0.9$ and $A_{\text{Fe}} = 1$ (Życki & Czerny 1994; George & Fabian 1991; hereafter GF91). The line becomes stronger with increasing Fe abundance (GF91). Here, we adopt the highest value of 1.5 keV for $A_{\text{Fe}} = 1$ and increase it with increasing $A_{\text{Fe}}$ according to the results of GF91. We find that already for $A_{\text{Fe}} = 1$, $\Omega/2\pi \sim 0.3$ at $\Delta \chi^2 \simeq +2$ (Table 6) which increase is not significant statistically. This means that the line emission from 3C 111 can originate from Compton reflection, but the $\Omega/2\pi \sim 0.3$ implies the reflector geometry is different from a slab.

We have tested whether ionization of the reflector can relax the constraints on the solid angle obtained above. We have found that the Ginga data cannot constrain the ionization parameter at all, but the best-fit $\xi = 0$. When we fix $\xi$ at a large value, e.g., $\xi = 5000$ erg s$^{-1}$ cm$^{-1}$, the allowed solid angle of the reflector decreases with respect to neutral reflection: $\Omega/2\pi = 0^{+0.09}_{-0.08}$. This decrease is a consequence of a larger depth of the K edge from an ionized medium than a neutral one with the data consistent with no K edge. Thus, the small values of $\Omega/2\pi$ obtained here are not an artefact of the assumption of the neutrality of the reflector. On the other hand, the reflected X-ray spectrum would have the same shape as the incident spectrum in the limit of complete ionization of all elements in the reflector (White, Lightman & Zdziarski 1988), which would then allow any value of $\Omega$, in particular $2\pi$. However, such strong ionization would lead to no Fe Kα line.

In fitting the ASCA data, we assumed the best-fit $\Omega/2\pi$ obtained from the Ginga data, which, due to the weakness of Compton reflection, affects little the fit. We find only a weak Fe K line in these data, with $W_{\text{Fe}} \sim 25^{+30}_{-25}$ eV, see Table 6 and Figure 3. Due to its weakness, the line parameters are not constrained, and $\sigma_{\text{Fe}}$ has been fixed at 0.1 keV while determining the confidence contours of other parameters.

We have investigated whether we could somehow miss a broad and strong Fe K line still present in the ASCA spectrum. First, we have found that the line disappears altogether from the model if Compton reflection is assumed to be strong, $\Omega/2\pi = 1$, which $\Omega$ is expected in the case of line formation in an inner region of an accretion disk. Second, we have considered the effect of using the SIS0 data obtained in the bright mode, which increases the exposure available for that detector by a factor of about 2.5 (but degrades the energy resolution, see Section 2). We find that then the Fe K line in the combined SIS/GIS data becomes only slightly stronger, with the best-fit $W_{\text{Fe}} \simeq 35$ eV. Again, the assumption of $\Omega/2\pi = 1$ results in disappearing of the line. If the SIS0 and SIS1 data are used without the GIS data (which have a worse energy resolution), $\sigma_{\text{Fe}} \sim 0.2^{+0.1}_{-0.2}$ keV, and the best-fit $W_{\text{Fe}} \simeq 60\,$–$\,$90 keV are obtained for $\Omega/2\pi$ between 1 and 0.12. Thus, any Fe K line in the data is at most moderate and its strong broadening is neither required nor implied by the data.

The ASCA data show little intrinsic spectral variability with respect to the Ginga data, see Table 6 and Figure 4. However, the ASCA data show a marked decrease of the absorbing column with respect to that seen by Ginga. This decrease correlates with the apparent decrease of the Fe K line flux between the Ginga and ASCA observations, which suggests the origin of the line primarily in the absorber. Although the best-fit value of $W_{\text{Fe}}$ from Ginga is a factor of $\sim 3$ larger than that expected from a shell of absorbing, isotropically-irradiated, matter with the best-fit value of $N_{\text{H}}$ (M86), the uncertainties on the line flux and on the reflector solid angle are such that comparable parts of the line can come from the absorber and the reflector. In that case a decrease of $N_{\text{H}}$ would lead to a noticeable decrease of $I_{\text{Fe}}$, explaining the weakness of the Fe K line in the ASCA data.

Figure 4 also shows the 1991–92 spectrum from OSSE. The OSSE spectrum, although not simultaneous with other observations presented here, is consistent with extrapolation of both the Ginga and ASCA power laws. Some spectral steepening at high energies is, however, possible. Fits to the combined Ginga/OSSE and ASCA/OSSE data yield $E_c = 1.6^{+6.0}_{-1.3}$ MeV and 300$^{+460}_{-130}$ keV, respectively. The models corresponding to the best-fit values of $E_c$ are plotted in Figure 4.

### 3C 390.3

The optical morphology of this powerful radio galaxy is unusual; there are no spiral arms, but the luminosity profile does not follow the $r^{1/4}$ law in the outer parts of the image (Smith & Heckman 1989). In the radio frequencies, the object is lobe-dominated and displays superluminal motion (Wamsteker & Clavel 1989 and references therein). The galaxy has been observed by EXOSAT, Ginga, ASCA, and OSSE.

We first analyze the spectra from Ginga, shown in Figure 5a. Our 1991 data exclude a period when a stellar flare occurred in the field of view of Ginga (Inda et al. 1994). The 1988 observation has been included in the NP94 sample, and the 1991 observation has been presented by Inda et al. (1994), who, however, have not searched for the presence of Compton reflection. We note a possible presence of a soft-excess component in the 1988 data, as indicated by the null value of the best-fit $N_{\text{H}}$ and positive residuals seen in the lowest Ginga channels (see Fig. 3 of Inda et al. 1994).
which is similar to the result of NP94 for the 1988 observation.

Table 7. Results of fits to the Ginga, ASCA and EXOSAT spectra of 3C 390.3. The fit to the 1993 November ASCA data set with Compton reflection is limited to the 3–10 keV energy range.

| A    | \(\alpha_s\) | \(N_H\) | \(E_b\) | \(\alpha\) | \(\Omega/2\pi\) | \(E_F\)  | \(\sigma_F\) | \(I_F\)  | \(W_F\)  | \(\chi^2/\text{dof}(\chi^2)\) |
|------|--------------|--------|--------|----------|---------------|--------|------------|--------|--------|-------------------|
|      |              |        |        |          | Ginga 1988 Nov |        |            |        |        |                   |
| 13.3 ±0.2 | -0.0 ±0.2  | -0.0 ±0.5 | -0.0 ±0.5 | 0.84 ±0.01 | 6.33 ±0.34 | 6.33 ±0.27 | 6.33 ±0.27 | 0.1f    | 2.1 ±1.4 | 58    | 34.8 ±35(1.25)   |
| 14.0 ±0.4 | -0.0 ±0.4  | -0.0 ±0.4 | -0.0 ±0.4 | 0.90 ±0.03 | 6.33 ±0.27 | 6.33 ±0.27 | 6.33 ±0.27 | 0.1f    | 3.4 ±1.3 | 67    | 28.1 ±34(0.88)   |
| 5.7 ±0.4  | -0.2 ±1.6  | -0.2 ±1.6 | -0.2 ±1.6 | 0.64 ±0.04 | 6.36 ±0.44 | 6.36 ±0.44 | 6.36 ±0.44 | 0.1f    | 2.5 ±1.4 | 84    | 31.2 ±35(0.89)   |
| 6.2 ±0.8  | -1.6 ±2.3  | -1.6 ±2.3 | -1.6 ±2.3 | 0.70 ±0.08 | 6.41 ±0.42 | 6.41 ±0.42 | 6.41 ±0.42 | 0.1f    | 2.7 ±1.4 | 86    | 29.0 ±34(0.85)   |
| 3.8 ±0.1  | -0.4 ±0.1  | -0.4 ±0.1 | -0.4 ±0.1 | 0.68 ±0.03 | 6.40 ±0.08 | 6.40 ±0.08 | 6.40 ±0.08 | 0.1f    | 2.0 ±1.2 | 240   | 1326 ±1314(1.01) |
| 3.9 ±0.4  | 0.74 ±0.04 | 0.74 ±0.04 | 0.74 ±0.04 | 0.54 ±0.05 | 6.38 ±0.06 | 6.38 ±0.06 | 6.38 ±0.06 | 0.1f    | 1.0 ±1.0 | 150   | 1309 ±1312(1.00) |
| 3.1 ±0.1  | -0.5f      | -0.5f   | -0.5f   | 0.56 ±0.06 | 6.38 ±0.06 | 6.38 ±0.06 | 6.38 ±0.06 | 0.1f    | 0.8 ±1.0 | 140   | 545 ±587(0.93)   |
| 4.5 ±0.2  | -0.8 ±0.2  | -0.8 ±0.2 | -0.8 ±0.2 | 0.70 ±0.04 | 6.44 ±0.11 | 6.44 ±0.11 | 6.44 ±0.11 | 0.1f    | 2.8 ±1.6 | 120   | 646 ±743(0.87)   |
| 7.8 ±0.4  | -0.1 ±0.1  | -0.1 ±0.1 | -0.1 ±0.1 | 0.77 ±0.03 | 6.75 ±0.39 | 6.75 ±0.39 | 6.75 ±0.39 | 0.1f    | 2.3 ±1.1 | 84    | 1048 ±1017(1.03) |
| 5.3 ±0.4  | -0.0 ±1.6  | -0.0 ±1.6 | -0.0 ±1.6 | 0.3f      | 5.91 ±0.91 | 5.91 ±0.91 | 5.91 ±0.91 | 0.1f    | 1.1 ±1.1 | 32    | 20/22(0.90)      |

1988 observation at the 99.99 per cent confidence level. (The top-layer Ginga data alone imply somewhat stronger reflection, with \(\Omega/2\pi = 0.50 ±0.26\) in 1988 and \(0.51 ±0.24\) in 1991, which values are still consistent within statistical errors with those in Table 7.)

We have also considered the effect of the reflector ionization. Similarly to the case of 3C 111, we find that ionization of the reflector has a negligible effect on \(\Omega\); \(\xi = 0.0\), which values are still consistent within statistical errors with those in Table 7.)

Results of ASCA observations of 3C 390.3 in 1993 and 1995 have been reported in Eracleous et al. (1996) and Leighly et al. (1997), respectively. Here, we reanalyse those data using the current version of the response and the effective area of ASCA (see Section 3). First, we fit the data from 1993 with a power-law continuum, a Gaussian line, and neutral absorption, see Table 7. Our results on both the continuum and the line are similar to those of Eracleous et al. (1996), in particular, \(\alpha \approx 0.7\) and \(\sigma_F \approx 0.2\) keV. However, the data show strong evidence for the presence of a soft excess, as demonstrated by a large reduction of \(\chi^2\) (by \(-17\) for addition of 2 parameters, which is significant at the 99.98 per cent confidence) when the power law is allowed to break. This is consistent with the possible presence of a soft X-ray excess in the 1988 Ginga data (see above) as well as in the EXOSAT data (Ghosh & Soundararajaperumal 1991). The broken power law model gives \(\alpha \approx 0.5-0.6\) above \(3\) keV, and the Fe line both weaker than for the single-power law fit as well as unresolved at the 1-\(\sigma\) level. The energy-width confidence contours and the line profile are shown in Figures 2 and 3, respectively.

As found above, the Ginga data above show the presence of Compton reflection. However, including it only weakly affects the results of the ASCA spectral fits, as shown in Table 7. The main effect is that the Fe K line becomes slightly weaker and narrower than in the case without Compton reflection. The ASCA spectrum modeled including Compton reflection is shown in Figure 5a.

Results similar to those discussed above are obtained
for the two ASCA observations of 1995. They are significantly shorter than that in 1993 (see Table 3), and thus constraints on the spectral parameters are weaker. We find those data do not require the presence of a spectral break in the continuum, i.e., the corresponding reductions in $\sigma$ are statistically insignificant. The $\text{Fe K}$ line is unresolved at the 1-$\sigma$ level whereas the continuum softens as the source brightens. The error bars are for the 1-$\sigma$ significance.

From Table 7, we see that the flux in the Fe line in all observations presented here is compatible with being constant, $\sim 3 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$, whereas the Fe-K ionizing flux ($\gtrsim 7 \text{ keV}$) varies by a factor of $\sim 2$, as illustrated in Figure 6a. The correlation coefficient between $I_{Fe}$ and the $7$–$10 \text{ keV}$ flux is $r = 0.16$, which corresponds to the probability that there is indeed no correlation between those quantities of $> 45$ per cent. This argues against the bulk of the line being due Compton reflection from an inner region of an accretion disk, in which case a proportionality of the line to the flux would be expected. Furthermore, $W_{Fe} \sim 100$–$150 \text{ eV}$ in the observations in 1993 and 1995 January cannot be accounted for by Compton reflection with $\Omega/2\pi \sim 0.3$ (e.g., GF91), seen in both Ginga observations. (Eracleous et al. 1996 claimed the Fe K line in the 1993 observation could be entirely due to Compton reflection without considering its strength measured by Ginga.) On the other hand, the absorbing column is so low that it can account for at most $W_{Fe} \sim 10 \text{ eV}$ (M86). Possible resolutions of this issue are discussed in Section 3 below.

Figure 6b shows that the X-ray spectrum softens when it brightens, as previously noted by Inda et al. (1994) and Leighly et al. (1997). This spectral variability yields spectra pivoting around $100 \text{ keV}$ at a flux corresponding to the average 1991–93 OSSE data, see Figure 5. The OSSE data at higher energies lie below the extrapolation of the X-ray power laws, which implies the presence of a high-energy cut-off or break. E.g., the 1988 Ginga data imply $E_c = 400^{+580}_{-170} \text{ keV}$ and the 1993 ASCA data yield $E_c = 260^{+320}_{-110} \text{ keV}$. Models with the high-energy cutoffs are plotted in Figure 5.

### 4.4 3C 382

The radio morphology of 3C 382 is typical for two-lobe sources with characteristic hot spots (McDonald, Kenderdine & Neville 1968). Optically, it appears as a distorted elliptical (Smith & Heckman 1989) with extremely broad Balmer lines reaching FWZI $\sim 25,000 \text{ km s}^{-1}$ (Osterbrock, Koski & Phillips 1975).

Ginga observed 3C 382 several times during 5 days in 1989 July (Kaastra, Kunieda & Awaki 1991). We have initially analyzed the Ginga spectra from the observation divided into 3 periods (as in Table 2). They are well described by a hard power-law spectrum with $\alpha \simeq 0.5$ with neither intrinsic absorption nor Compton reflection and are almost identical. Therefore, we consider hereafter only the total spectrum. Table 8 gives the fit results, and Figure 7 shows the unfolded spectrum and the best-fit model. We see that allowing for the presence of Compton reflection does not improve the fit, and $\Omega/2\pi \lesssim 0.3$. (With the top-layer data only, a weaker constraint is obtained, $\Omega = 0.22^{+0.53}_{-0.22}$.) This differs from the corresponding fit in NP94, who obtained $\Omega/2\pi \gtrsim 1$. However, the reflection model of NP94 includes the Fe K line tied to the reflection continuum (as in our models below) and the strong reflection in their fits is driven by the large flux in the line. Similarly as for 3C 111 and 3C 390.3, ionization of the reflector leads to a reduction of the fitted reflection strength; for a large $\xi = 5000 \text{ erg s}^{-1} \text{ cm}^{-1}$, $\Omega/2\pi = 0^{+0.15}_{-0.03}$.

On the other hand, there is a pronounced Fe K line with $W_{Fe} \simeq 220 \text{ eV}$ in the data. We find that this line is too strong to be explained by Compton reflection. Namely, when we tie the strength of the Fe line to the solid angle of the reflector (as in Section 3.2), the fit becomes significantly worse than in the case of the free line flux, even for the Fe abundance 4 times the solar value (Table 8).

Kaastra et al. (1991) have found the presence of a soft excess in the Ginga spectrum. We also see a similar component in our data. However, our analysis is constrained to the range $\gtrsim 1.7 \text{ keV}$ whereas Kaastra et al. also included the 1.2–1.7 keV Ginga channel (which calibration is in general less certain for weak sources). Thus, we do not attempt to constrain the form of the excess with the Ginga data.

A soft excess is seen very pronouncedly in the EXOSAT data (Ghosh & Soundararajaperumal 1992), which we also find in the average EXOSAT data, see Table 8 and Figure 7. Namely, the fit improves with $\Delta \chi^2 = -11$ (corresponding to the statistical significance of 99 per cent) when a break in the power law spectrum is allowed. The continuum slope
Results of fits to the Table 8. Results of fits to the Ginga, EXOSAT and ASCA spectra of 3C 382. The second fit with $I_{\text{Fe}}/\Omega = \text{const}$ is for $A_{\text{Fe}} = 4$.

| $A$ | $\alpha_\text{K}$ | $N_\text{H}$ | $E_\text{b}$ | $\alpha$ | $\Omega/2\pi$ | $E_{\text{Fe}}$ | $\sigma_{\text{Fe}}$ | $I_{\text{Fe}}$ | $W_{\text{Fe}}$ | $\chi^2$/dof($\chi_\text{b}^2$) |
|-----|----------------|--------------|-------------|--------|---------------|-------------|---------------|-----------|----------|-----------------|
| 2.4$^{+0.1}_{-0.1}$ | - | 0.0$^{+1.4}_{-2.0}$ | - | 0.5$^{+0.06}_{-0.04}$ | 0.05$^{+0.28}_{-0.05}$ | 6.52$^{+0.20}_{-0.20}$ | 0.1f | 3.7$^{+1.1}_{-1.2}$ | 220 | 29.6/34(0.87) |
| 3.0 | - | 3.2$^{+2.9}_{-2.6}$ | - | 0.6$^{+0.11}_{-0.11}$ | 0.89$^{+0.52}_{-0.29}$ | 6.59$^{+0.26}_{-0.26}$ | 0.1f | 2.5$^{+1.5}_{-2.5}$ | 160 | 47/35(1.35) |
| 2.5 | - | 0.0$^{+2.2}_{-2.2}$ | - | 0.5$^{+0.05}_{-0.04}$ | 0.75$^{+0.25}_{-0.25}$ | 6.57$^{+0.24}_{-0.24}$ | 0.1f | 3.0$^{+1.0}_{-1.0}$ | 190 | 35/35(0.99) |
| 9.6 | - | 0.0$^{+0.3}_{-0.3}$ | - | 0.6$^{+0.03}_{-0.02}$ | 0f | 5.89$^{+0.06}_{-0.02}$ | 0.1f | 3.5$^{+2.2}_{-2.3}$ | 72 | 29/21(1.38) |
| 9.3 | 0.76$^{+0.19}_{-0.05}$ | 0.0$^{+2.2}_{-2.2}$ | 3.7$^{+2.2}_{-1.2}$ | 0.59$^{+0.31}_{-0.23}$ | 0f | 5.35$^{+0.05}_{-0.05}$ | 0.1f | 1.7$^{+4.6}_{-1.7}$ | 30 | 17.8/19(0.94) |

| $A$ | $\alpha_\text{K}$ | $N_\text{H}$ | $E_\text{b}$ | $\alpha$ | $\Omega/2\pi$ | $E_{\text{Fe}}$ | $\sigma_{\text{Fe}}$ | $I_{\text{Fe}}$ | $W_{\text{Fe}}$ | $\chi^2$/dof($\chi_\text{b}^2$) |
|-----|----------------|--------------|-------------|--------|---------------|-------------|---------------|-----------|----------|-----------------|
| 14.0$^{+0.2}_{-0.3}$ | - | 0.3$^{+0.1}_{-0.2}$ | - | 1.0$^{+0.05}_{-0.04}$ | 0f | 6.57$^{+0.91}_{-0.46}$ | 2.34$^{+1.17}_{-0.56}$ | 54$^{+66}_{-56}$ | 1400 | 1611/1610(1.00) |
| 13.7$^{+0.4}_{-0.4}$ | 0.97$^{+0.04}_{-0.03}$ | 0.2$^{+0.4}_{-0.1}$ | 3.6$^{+0.5}_{-0.5}$ | 0.65$^{+0.07}_{-0.07}$ | 0f | 6.30f | 0f | 1.3$^{+1.5}_{-1.3}$ | 27 | 1609/1610(1.00) |

Figure 7. The X-ray spectra of 3C 382 from ASCA, EXOSAT and Ginga (from top to bottom).

above the break becomes then similar that for the Ginga data.

We then consider the ASCA spectrum of 3C 382. We find that adding a soft excess (using a model with a broken power law) results in a slight improvement of the fit over the model with a single power-law continuum, as shown in Table 8. However, the two models yield vastly different results regarding the Fe K line. The single-power law model requires the line to be very strong, $W_{\text{Fe}} \gtrsim 1$ keV, and very broad, $\sigma_{\text{Fe}} \sim 2-3$ keV (as found before by Reynolds 1997). The line flux is then $\sim 15$ times larger than that in the Ginga data. Also, the spectral index is much softer than that observed from the source in all previous EXOSAT and Ginga observations (Ghosh & Soundararajaperumal 1992; Kaastra et al. 1991). The extremely large $\sigma_{\text{Fe}}$ would require the line origin from reflection in inner parts of an accretion disk disk (e.g., Fabian et al. 1995), for which, however, the expected $W_{\text{Fe}}$ is at least several times less. Also, the weakness of the continuum reflection seen in the Ginga data appears to rule out a reflecting inner disk.

However, the Fe K line becomes very weak as well as unresolved in the broken power-law model, and the hard power-law index becomes similar to that observed before by EXOSAT and Ginga. Also, the line flux in the ASCA observation becomes then compatible within statistical errors with that measured by Ginga. The line parameters are not constrained due to the weakness of the line, and thus $E_{\text{Fe}}$ and $\sigma_{\text{Fe}}$ have been fixed at the best-fit values while determining the confidence regions of other parameters in this fit (Table 8). Since the Ginga data show reflection to be very weak, we do show here results of a fit with Compton reflection. The resulting line profile is shown in Figure 3.

We interpret the similar $\chi^2$ in both above fits to the ASCA data as simply due to the very broad and strong Fe K line in the first fit giving the dominant continuum component above 7 keV, whereas that continuum is accounted for by the harder power law in the second fit. This discrepancy illustrates the importance of careful modeling of the continuum for determination of parameters of Fe K lines in ASCA data, which energy range extends only slightly above the energy range dominated by the Fe K line.

We have also analyzed the ASCA SIS data of 3C 382 obtained in the bright mode, which results in a substantially longer exposure for the SIS detectors but somewhat worse energy resolution (see Section 2). We have found that the results reported in Table 8 remain virtually unchanged. In particular the broken power law model yields only a narrow and weak Fe K line with the best-fit $\sigma_{\text{Fe}} = 0$ keV and $W_{\text{Fe}} = 28$ eV. However, another minimum with almost the same $\chi^2$ is present, at which the line is broad with $\sigma_{\text{Fe}} \sim 1.4$ keV and $W_{\text{Fe}} \sim 230$ eV. This would suggest that reflection from an inner disk may be present. However, when $\Omega/2\pi$ is fixed at 1, corresponding to disk reflection, the line width becomes constrained to $\sigma_{\text{Fe}} \lesssim 0.6$ keV with the best fit at $\sigma_{\text{Fe}} \sim 0$ keV and $W_{\text{Fe}} \simeq 30$ eV. Thus, the presence of a strong and broad Fe K line appears unlikely.

Figure 7 shows that the X-ray continuum of 3C 382 is strongly variable, with the 2-keV flux changing by an order of magnitude between the Ginga and ASCA observations. The spectral variability is similar to that seen 3C 390.3, namely the spectrum softens with increasing X-ray flux as well as the Fe K line flux is, within the statistical errors, compatible with constant. The line is thus unlikely to be due to reflection from an inner disk, and probably originates at large distances where the variable continuum is averaged due to large light-travel time across the region of line formation. However, the Fe K line-emitting region has to be out of the line of sight as the line strength is much too large (M86) to be due to the weak absorption in this object.
line is very strong, $W_{\text{Fe}} \simeq 1$ keV, and broad, $\sigma_{\text{Fe}} \simeq 2$ keV (as obtained before by Reynolds 1997). On the other hand, the line strength becomes moderate, $W_{\text{Fe}} \simeq 100$ eV, and relatively narrow, when the power-law continuum is allowed to break. The spectrum corresponding to the latter model is plotted in Figure 8a. Allowing a break in the power law also improves the fit at the significance of 99.6 per cent. Thus, the very strong and broad line obtained for a single power-law fit seems to be an artefact of underestimating the continuum around the line in this model.

The presence of a soft excess in 3C 120 is confirmed by Grandi et al. (1997), who analyzed ROSAT PSPC observations from 1993. Those data, when fitted by a power law, show $\alpha \sim 2-3$ in the 0.15–2.1 keV range. This argues in favour of the broken power-law model for the ASCA data and against the reality of the very strong and broad Fe K line obtained assuming no soft excess. Also, the averaged EXOSAT data yield almost the same parameters for the broken-power law model as the ASCA data, although those parameters are only weakly constrained.

The line parameters depend somewhat on the presence of Compton reflection. Table 9 also presents results of a fit with the assumed $\Omega/2\pi = 1$ to the 4–10 keV data. The line becomes then even weaker and narrower than for the broken-power law model without reflection. The confidence contours for $E_{\text{Fe}}$ and $\sigma_{\text{Fe}}$ and the line profile are shown in Figures 2 and 3, respectively. Note that this fit yields a small $W_{\text{Fe}} \simeq 60$ eV, which is not compatible with theoretical predictions (GF91; Życki and Czerny 1994) for the line strength from this process of $W_{\text{Fe}} \sim 150$–200 eV (unless the reflector is so strongly ionized that resonant absorption suppresses the line), which argues against $\Omega/2\pi \gtrsim 1$ in 3C 120.

The ASCA spectrum of 3C 120 has also been fitted in the 3–10 keV range (without including reflection) by Nandra et al. (1997). They obtained a Gaussian line with $\sigma_{\text{Fe}} = 0.74^{+0.34}_{-0.27}$ keV and $W_{\text{Fe}} = 330^{+200}_{-130}$ eV, and the power-law index of $\alpha = 0.89^{+0.08}_{-0.06}$ (their confidence regions are for $\Delta \chi^2 = 4.7$). To enable a precise comparison of the results, we have also performed a fit with a power-law model in the 3–10 keV range, and obtained results virtually identical to those for the broken-power law fit presented in Table 9, e.g., $\sigma_{\text{Fe}} = 0.28^{+0.96}_{-0.24}$ keV and $W_{\text{Fe}} \simeq 100$ eV. Thus, we find the Fe K line to be significantly narrower and weaker than that found by Nandra et al. (1997) for the same model and the same energy range used. This difference is apparently caused by an older version of the ASCA response and effective area used by those authors (of 1995, whereas we use the release of 1997). To study the issue further, we have also used the ASCA data on 3C 120 obtained with the data processing package of 1996 March-April. We have found very little difference with respect to our current results, e.g., $\sigma_{\text{Fe}} = 0.26^{+0.76}_{-0.17}$ keV and $W_{\text{Fe}} \simeq 90$ eV for the power-law model in the 3–10 keV range. This demonstrates the importance of updating the results on the Fe K line parameters obtained with the pre-1996 data-processing software.

This conclusion is further reinforced by a comparison of our results with those of Grandi et al. (1997). They have fitted the 0.6–10 keV ASCA spectrum with a broken power-law continuum model. They found the break energy of 4 keV, similarly to our results (Table 9). However, they obtained the parameters very similar to those of Nandra et al. (1997), $\sigma_{\text{Fe}} = 0.71^{+0.24}_{-0.25}$ keV (in the source frame), $W_{\text{Fe}} = 280^{+160}_{-80}$ eV.

Figure 8. (a) The spectra of 3C 120 from ASCA (the upper X-ray spectrum), EXOSAT (the lower X-ray spectrum), and OSSE (> 50 keV). The solid and dashed curves correspond to model with a broken power law and an exponential cutoff fitted to the ASCA/OSSE and EXOSAT/OSSE data, respectively. (b) The spectrum of 3C 120 from contemporaneous observations by ASCA (1994 February 17) and OSSE (1994 February 17–March 1). The same model form as in (a) was fitted to the data.

4.5 3C 120

3C 120 is a BLRG exhibiting characteristics intermediate between those of FR I galaxies and BL Lacs (Urry & Padovani 1995). It is highly variable in all energy bands, and shows superluminal motion in the VLBI core (Muxlow & Wilkinson 1991; Walker, Benson & Unwin 1988; Walker, Walker & Benson 1988).

3C 120 has been observed by EXOSAT (Maraschi et al. 1991) and ASCA, but not by Ginga. Thus, we have no reliable information on the presence of Compton reflection in this object. 3C 120 was observed by HEAO-1, and the A2 data imply a reflector solid angle of $\Omega \simeq (1^{+3}_{-1}) \times 2\pi$ (rescaling the results of Weaver, Arnaud & Mushotzky 1995 obtained for angle-averaged reflection into an inclination of 30°), i.e., the measurement errors are large for those data. Also, the A2 results for reflection in other AGNs (Weaver et al. 1995) correspond to solid angles systematically larger than those from Ginga (NP94). Taking into account those uncertainties, we compute below the spectral parameters for ASCA and EXOSAT data for both $\Omega = 0$ and $\Omega/2\pi = 1$.

Table 9 gives fit results to the ASCA spectrum. Similarly to the case of 3C 382, we find the fitted line parameters depend very strongly on the way the continuum is modeled. If we model the ASCA continuum as a single power law, the
The 4–10 keV range.

Results of fits to the Table 9.

explained by an earlier version of the processing software model in Table 9. These differences can again be entirely and the hard continuum softer than those found for the same

ken power law multiplied it by an exponential factor. The spectrum. We used a continuum model consisting of a bro-

tows us to study the presence of a high-energy cutoff in the spectrum. We can further constrain the presence of a cutoff by

fitted by them by a softer power law than ours (due to an

our by a factor of

10 keV changes within a factor of several. This

also gives the e-folding energies obtained using the available

OSSE data, and the corresponding X\gamma intrinsic luminosities.

We see that the continuum Compton reflection is either ab-

sent or weak but the Fe K line flux is often much stronger than that expected from the weak reflection. Furthermore,

this is the case in both objects with weak absorption in the line of sight and in 3C 445, which has strong ($N_H \gtrsim 10^{23}$

cm$^{-2}$) absorption.

In 3C 445, the Fe K line can be explained entirely by ab-

sorption, and Compton reflection is constrained to be weak, $\Omega/2\pi \lesssim 0.2$. In 3C 111, $\Omega/2\pi \lesssim 0.4$, and the flux in the Fe K line can be in principle explained by the sum of the con-

tributions from the observed absorption and Compton re-

fection. The only object with Compton reflection detected unambiguously is 3C 390.3, in which $\Omega \sim 0.3$ was detected with a 99.99 per cent significance in one \textit{Ginga} observation. However, the Fe K line strengths in two \textit{ASCA} observations of this object were too large to be explained by that reflection (as well as absorption was negligible). In 3C 382, $\Omega/2\pi \lesssim 0.3$ was obtained from the \textit{Ginga} observation, but the line flux in that observation was much too large to be explained by either reflection or (negligible) absorption. In 3C 120, Compton reflection has not been measured. How-

ever, $\Omega/2\pi \sim 1$ appears unlikely based on the weakness of the Fe K line implied by a model with strong reflection.

The observed variability also indicates the origin of the Fe K line different than from Compton reflection from an accretion disk. Namely, the line flux in repeated observations of 3C 390.3 and 3C 382 over several years by \textit{Ginga} and \textit{ASCA} is compatible with being constant whereas the flux around 10 keV changes within a factor of several. This disagrees with the origin of the line from the hard X-ray continuum incident on an accretion disk.

Furthermore, all but one \textit{ASCA} observations show the lines are consistent with being unresolved with respect to the continuim fitted above $\sim 3$ keV. Thus, these data provide no compelling argument for the origin of the lines in inner accretion disks, consistent with the weakness of reflection and the lack of line variability. A possible exception is 3C 120, in which the broken-power law model without reflection yields the line being moderately broad, see Table 10. We note that if the 0.5–10 keV continuum in 3C 382 and 3C 120 is forced to be a single power law, the fitted lines become resolved and much stronger, with $\sigma_{Fe} \sim 2$ keV and $W_{Fe} \sim 1$ keV. However, this appears to be an artefact of neglecting the soft X-ray excesses present in BLRGs (observed by, e.g., \textit{EXOSAT} and \textit{ROSAT}).

Table 10 also shows results of fitting the X-ray data of 3 objects together with the OSSE data (not simultaneous)
Table 10. Summary of main parameters of BLRGs. The statistical significance of the presence of an Fe K line is given by $P$, where $1 - P$ given below is the probability that there is no line in the data. The e-folding energy, $E_c$, is obtained using the average OSSE data when the data exist and assumed to be 400 keV otherwise, and $L$ is the absorption-corrected 1–1000 keV isotropic luminosity corresponding to that model in units of $10^{44}$ erg s$^{-1}$ (assuming $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$).

| Object | Instrument | $\alpha$ | $\Omega/2\pi$ | $W_{Fe}$ | $\sigma_{Fe}$ | $1 - P$ | $E_c$ [keV] | $L$ |
|--------|------------|---------|-------------|--------|-------------|--------|------------|----|
| 3C 445 | Ginga      | 0.45$^{+0.14}_{-0.10}$ | 0.0$^{+0.22}_{-0.10}$ | 150    | 0.1f        | –      | 400f       | 13.5 |
|        | ASCA       | 0.39$^{+0.28}_{-0.29}$ | 0$^{+0.18}_{-0.12}$ | 140    | 0$^{+0.18}_{-0.12}$ | 1.4 $\times$ 10$^{-3}$ | 400f | 29.4 |
| 3C 111 | Ginga      | 0.82$^{+0.08}_{-0.06}$ | 0.12$^{+0.31}_{-0.12}$ | 78     | 0.1f        | 0.037  | 1600$^{+1000}_{-1400}$ | 10.0 |
|        | ASCA       | 0.73$^{+0.03}_{-0.02}$ | 0.12f       | 25     | 0$^{+\infty}_{-\infty}$ | 0.73   | 300$^{+1300}_{-1300}$ | 9.2  |
| 3C 390.3 | Ginga    | 0.90$^{+0.08}_{-0.08}$ | 0.35$^{+0.15}_{-0.24}$ | 67     | 0.1f        | 4.7 $\times$ 10$^{-4}$ | 400f | 11.6 |
|        | ASCA       | 0.54$^{+0.05}_{-0.07}$ | 0f         | 150    | 0$^{+0.10}_{-0.12}$ | 5.6 $\times$ 10$^{-8}$ | 260$^{+1300}_{-1300}$ | 7.8  |
| 3C 382 | Ginga      | 0.70$^{+0.04}_{-0.03}$ | 0.35f       | 120    | 0$^{+0.33}_{-0.0}$ | 0.016  | 620$^{+3600}_{-3600}$ | 8.7  |
|        | ASCA       | 0.77$^{+0.03}_{-0.03}$ | 0.35f       | 84     | 0$^{20.3_{-10.0}}_{-2.0}$ | 0.28   | 300$^{+300}_{-300}$ | 9.8  |
| 3C 120 | ASCA       | 0.72$^{+0.07}_{-0.06}$ | 0f         | 110    | 0.32$^{+0.76}_{-0.20}$ | 3.0 $\times$ 10$^{-5}$ | 130$^{+200}_{-140}$ | 3.8  |

Figure 9. The average Ginga spectrum of 3C 111, 3C 382, and 3C 390.3, and the average OSSE spectrum of 3C 111, 3C 120, and 3C 390.3. The Ginga spectrum is fitted by the model with a power-law incident continuum plus Compton reflection and the Fe K line (solid curve). The dashed curve gives the power-law fit to the OSSE spectrum.

With an e-folded power law continuum. We note that in all cases, the OSSE data lie on or below the extrapolated X-ray continuum (initially fitted without the OSSE data), in spite of strong variability of both the X-ray flux and spectral index. This argues strongly for the presence of soft $\gamma$-ray spectral breaks in those spectra.

5.2 The average X-ray properties

The average hard X-ray spectral index of the studied objects is $\sim 0.7$ for observations by all the three considered instruments, Ginga, ASCA, and EXOSAT. When Compton reflection is included, the average $\alpha$ from the Ginga observations is 0.67 with a dispersion of 0.18. Similar values are obtained for the EXOSAT and ASCA observations. Only the Ginga data constrain the relative strength of Compton reflection. The unweighted average for the 5 observations of the 4 BLRGs is $\Omega/2\pi = 0.16$.

Very similar results to those above are also obtained for the average Ginga spectrum of BLRGs, see Figure 9 and Table 11 (excluding 3C 445 due to the contamination of its spectrum by a cluster as well as due to its strong intrinsic absorption). The average values of $z$ and $N_{H_\alpha}$ for the sample have been used. If only the top-layer Ginga data are used, $\Omega = 0.09^{+0.25}_{-0.05}$ is found, i.e., very similar to that given in Table 11.

We stress that the average continuum properties of our sample are thus distinctly different from those of the sample of Seyfert 1s of NP94, which is strongly dominated by radio-quiet objects (although it also includes 3C 111, 3C 382, and 3C 390.3). For those objects, the average $\alpha = 0.95$ with a dispersion of 0.15 and the average solid angle of the Compton reflector (in fits with a Fe K line independent of the continuum reflection) is $\Omega/2\pi = 0.52$ with a dispersion of 0.18. So the two samples are distinctly different statistically.

In spite of the weak reflection in BLRGs, the Ginga and ASCA data show in many cases strong Fe K lines in the spectra, with the average equivalent width of 100 eV. This equivalent width clearly cannot be explained by the weak Compton reflection observed (e.g., GF91).

5.3 The soft $\gamma$-ray properties

OSSE has observed 3 BLRGs until 1997, see Table 4. Table 4 also gives the values of the spectral index for fits with a power law, which are plotted in Figure 10. Although the individual determinations of $\alpha$ bear large statistical errors, both the average $\alpha = 1.17 \pm 0.16$, and the $\alpha$ fitted to the average OSSE spectrum, see Table 11 and Figure 9, are significantly larger than the X-ray spectral indices. Since Compton reflection is weak in BLRGs, the difference between the spectral indices clearly shows the existence of a break around $\sim 100$ keV in the intrinsic soft $\gamma$-ray spectrum, see Figure 9.

Interestingly, the average OSSE spectrum of BLRGs is itself fully consistent with a power law and does not show any evidence for curvature. When the power law model is replaced by an e-folded power law, there is no improvement of the fit ($\Delta \chi^2 < 1$ for addition of one parameter). Thus, there is no evidence for a high-energy cutoff in the power law above $\sim 100$ keV (apart from the spectral break at that...
energy implied by the extrapolated X-ray spectra). This contrasts the case of radio-quiet Seyferts 1s and 2s, which average OSSE spectra show spectral curvature at very high significance: $\chi^2_{\nu} = 1.4$ for a power law fit and 0.9 for an e-folded power law fit (Johnson et al. 1997).

A break at $\sim 100$ keV is also indicated by the simultaneous ASCA/OSSE observation of 3C 120 (see Section 13). To further constrain the presence of a break, we have also obtained the average $X_\gamma$ spectra of BLRGs observed by both Ginga and OSSE (3C 111 and 3C 390.3; Z95), and EXOSAT and OSSE (3C 120 and 3C 390.3). In fits, we use the average values of $z$ and $N_{\text{H,G}}$ from Table 1 for each pair. Since the number of OSSE observations is limited for those samples, we allow for free normalization of the OSSE data with respect to the other data sets.

We have fitted the spectra with e-folded power laws and Compton reflection, and with broken power laws, and found that the latter model provides a better fit ($\Delta \chi^2 = -6$ and $-2$ for Ginga/OSSE and EXOSAT/OSSE, respectively). Results of the fits with that model are given in Table 11 and Figure 11 (the EXOSAT/OSSE data are best-fitted with $N_H = 0$). The fits confirm the presence of breaks in those spectra around $\sim 100$ keV although the form of the break is relatively poorly constrained. A single power-law model is ruled out at a high significance, $\Delta \chi^2 = +10$ and $+6$ for the Ginga/OSSE and EXOSAT/OSSE data, respectively.

Finally, we also fit together the average Ginga and OSSE spectra of all available objects, shown in Figure 9, see the last row of Table 11. Again an e-folded power law model provides a worse fit than a broken power law, and the break energy is at $\sim 100$ keV.

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**Table 11.** Fits to the average Ginga, OSSE and EXOSAT spectra of BLRGs.

| $A$ | $\alpha$ | $N_{\text{H}}$ | $E_b$ | $\Omega/2\pi$ | $\alpha_b$ | $E_{\text{Fe}}$ | $I_{\text{Fe}}$ | $W_{\text{Fe}}$ | $\chi^2/\text{dof}(\chi^2_{\nu})$ |
|-----|---------|--------------|------|---------------|---------|-------------|------------|--------|------------------|
| 5.5 | $0.67^{+0.05}_{-0.04}$ | $1.5^{+1.0}_{-1.1}$ | $0.08^{+0.17}_{-0.08}$ | 6.49$^{+0.13}_{-0.14}$ | 3.4$^{+0.7}_{-0.7}$ | 130 | 35/34(1.02) |
| 46.7 | $-0.05$ | $-0.07$ | $-0.09$ | 1.15$^{+0.25}_{-0.28}$ | $-0.08$ | 35/38(0.97) |
| 9.2 | $0.76^{+0.02}_{-0.02}$ | $2.5^{+0.7}_{-0.7}$ | $95^{+20}_{-25}$ | $2.14^{+1.10}_{-0.90}$ | $6.46^{+0.18}_{-0.17}$ | 3.1$^{+0.9}_{-0.8}$ | 80 | 50/78(0.65) |
| 10.6 | $0.77^{+0.02}_{-0.02}$ | $80^{+35}_{-73}$ | 0.9 | $1.52^{+1.20}_{-0.55}$ | $5.9^{+0.4}_{-0.5}$ | 3.9$^{+1.9}_{-1.9}$ | 76 | 49/54(0.90) |
| 5.4 | $0.67^{+0.02}_{-0.02}$ | $1.2^{+1.0}_{-0.7}$ | $93^{+20}_{-28}$ | $1.66^{+1.02}_{-0.55}$ | $6.47^{+0.14}_{-0.13}$ | 3.4$^{+0.8}_{-0.7}$ | 130 | 66/70(0.94) |

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**Figure 10.** The distribution of the 50–500 keV energy spectral index in OSSE observations of BLRGs. The vertical dashed line corresponds to the weighted average of $\alpha$. The filled circles, squares and triangles with error bars correspond to the fits in Table 4 for 3C 111, 3C 120, and 3C 390.3, respectively.

**Figure 11.** The average spectrum of 3C 111 and 3C 390.3 from Ginga/OSSE (top) and of 3C 120 and 3C 390.3 from EXOSAT/OSSE (bottom). The solid curves correspond to the model with a broken power law and an Fe K line.
6 COMPARISON WITH Cen A

Cen A (NGC 5128) is the nearest active galaxy at $z = 0.0008$ and with $N_{H,CL} = 7 \times 10^{20} \, \text{cm}^{-2}$ (Stark et al. 1992). No broad line emission can be observed from this giant elliptical radio galaxy due to heavy absorption in a warped dusted lane viewed close to edge-on, and thus it is not a BLRG. On the other hand, the unified AGN model (e.g., Antonucci 1993) postulates that the difference between AGNs with and without broad lines is solely due to the viewing angle of the nucleus. Since Cen A is one of the brightest extragalactic X-ray sources, we can determine with high accuracy its X$\gamma$ properties despite the relatively large absorbing column density, in particular, the presence of Compton reflection and a high-energy break. We can then compare these properties with those obtained in this work for BLRGs, with the goal to test the unified AGN model.

We use here the Ginga spectrum of Cen A of 1989 March 8 (Miyazaki et al. 1996; Warwick et al. 1998). We note that Cen A exhibits a strong and complex soft X-ray components due to the jet and diffuse emission (observed by ROSAT) as a soft power law and 2 hot-plasma components following Turner et al. (1997). The primary nuclear continuum is modeled by a power law including reflection absorbed by a column, $N_{H,1}$. The viewing angle of the reflection component is taken as 70$^\circ$ (Graham 1979; Dufour et al. 1979). The nucleus continuum itself shows a soft X-ray excess, which we model here as a power law with the same $\alpha$ but absorbed by a lower column, $N_{H,2}$, following Warwick et al. (1998) and Turner et al. (1997). This provides a good fit to the Ginga spectrum, and fit results are presented in Table 12. We see that Compton reflection is at most weak, similar to results of Miyazaki et al. (1996) and Warwick et al. (1998). (If only the top-layer data are used, $\Omega/2\pi = 0^{+0.15}_{-0.15}$, identical to the result in Table 12.) The Fe K line in the spectrum can be explained as due to fluorescence in the absorbing column, $N_{H}$ (M86). Note that when the Fe K/$\alpha$ Ni K line are included in the model (as for the ASCA data, Section 3), $E_{Fe} \simeq 6.4 \pm 0.1 \, \text{keV}$ and $\sigma_{Fe} \simeq 0^{+0.4}_{-0.4}$ keV. The line is thus compatible with being narrow, as confirmed using ASCA data by Turner et al. (1997). We also note that our results on the hard continuum are rather independent of the assumed form of the soft X-ray excess, which is only weakly constrained by the Ginga data. For example, we have obtained almost identical results as above by modeling the entire soft component as bremsstrahlung at $kT = 1.65 \, \text{keV}$, which was used in fitting EXOSAT data on Cen A by Morini, Anselmo & Molteni (1989).

OSSE observed repeatedly Cen A during 1991–94 (Kinzer et al. 1995). The soft $\gamma$-ray flux varied within a factor of two. All the spectra showed distinct spectral breaks. When the spectra were fitted with a broken power law, the break energy was $\sim 140–170 \, \text{keV}$. The power law below the break was $\alpha \sim 0.7$ (only slightly harder than that seen by Ginga in 1991). A similar break energy of 180 keV was found in a balloon observation (Miyazaki et al. 1996). The hard power law seen by OSSE above the break was found to continue without any further break to $\sim 10 \, \text{MeV}$ by the COMPTEL detector aboard CGRO (Steinle et al. 1997), as illustrated in Fig. 6 of Johnson et al. (1997). However, a spectral softening above $\sim 10 \, \text{MeV}$ is required by the $> 100 \, \text{MeV}$ flux measured from Cen A by EGRET (see Steinle et al. 1997).

Thus, we find that the X-ray spectral index, the tight limit on Compton reflection, and the spectral break around $\sim 150 \, \text{keV}$ in Cen A are very similar to those found in our sample of BLRGs. (Unfortunately, no useful constraints on the spectra above 1 MeV can be obtained for BLRGs). This similarity is strongly suggestive of the common nature of the radiative processes in both narrow-line and broad-line radio galaxies, as expected in the AGN unified model.

7 DISCUSSION

7.1 The origin of the Fe K$\alpha$ line

Our results clearly show that the bulk of the Fe K line flux in our sample of BLRGs is unlikely to be due to Compton reflection, which is weak (or absent) in the studied objects. In 3C 445, the line can be satisfactorily explained by strong absorption in the line of sight, with $N_H > 10^{23} \, \text{cm}^{-2}$. This is also the case in our comparison narrow-line object, Cen A. On the other hand, absorption in the line-of-sight in 3C 111, 3C 120, 3C 382, and 3C 390.3 is too weak to be able to explain the observed line fluxes.

However, the observed line fluxes can be satisfactorily explained in those objects if there is matter with $N_H > 10^{23} \, \text{cm}^{-2}$ covering a large solid angle, $\Omega$, outside our line of sight. Such matter can be identified with molecular torii, common in AGNs. Irradiation of this matter by a power law spectrum with the 1-keV normalization, $A$, and the energy spectral index, $\alpha$, gives rise to a flux in the Fe K line of approximately

$$ I_{Fe} \approx \frac{1.7 A_{Fe}}{\alpha + 3} \frac{\Omega}{4\pi} Y A \min \left( \tau_T, \frac{0.5}{A_{Fe}} \right) \left( \frac{1 \, \text{keV}}{E_{Fe}} \right)^{1+\alpha}, $$

where $1.7 A_{Fe}$ is the ratio of the Fe K-edge cross section (at $E_{Fe}$) times the relative Fe abundance to the Thomson cross section, $Y \sim 1/2$ is the fluorescence yield, and $\tau_T$ is the Thomson optical depth of the medium (see Krolik & Kallman 1987). At $\tau_T > 0.5/A_{Fe}$, the K-edge optical...
Table 12. Results of the fit to the Ginga spectrum of Cen A. The model also includes 3 fixed components, see text. $W_{Fe}$ is given with respect to the total absorbed continuum.

| $A_i$ | $N_{H,i}$ | $\alpha$ | $\Omega/2\pi$ | $E_{Fe}$ | $\sigma_{Fe}$ | $I_{Fe}$ | $W_{Fe}$ | $\chi^2$/dof($\chi^2$) |
|-------|-----------|----------|---------------|--------|-------------|--------|---------|---------------------|
| $120^{+10}_{-10}$ | $10^{+10}_{-10}$ | $10.0^{+1.2}_{-1.0}$ | $0.79^{+0.06}_{-0.05}$ | $0.15$ | $6.49^{+0.11}_{-0.11}$ | $42^{+8}_{-9}$ | $130^{+25}_{-25}$ | $40/39(1.03)$ |

Figure 13. A contribution to the spectrum of a BLRG (as illustrated by the average Ginga spectrum) from Thomson scattering in a medium with $N_{H} = 2 \times 10^{23}$ cm$^{-2}$ covering a 3r solid angle as seen from the nucleus (dotted curve). The medium is outside of the line of sight and thus it does not absorb the direct continuum with assumed no reflection (dashed curve). The solid curve gives the sum.

depth exceeds unity and the line flux approximately saturates. For the average Ginga spectrum of BLRGs (Table 11), $(\Omega_o/4\pi)A_{Fe}$ is required to account for the observed Fe K line. This is compatible with the $N_{H}$ observed in 3C 445 and Cen A.

Such a medium will also give rise to a scattered continuum component, approximately given by $(\Omega_o/4\pi)A_{Fe}$ times the observed direct continuum, where $\tau_{o}(E)$ is the bound-free optical depth of the surrounding medium. The presence of such a continuum component is allowed by the X-ray data (but only weakly constrained). Figure 13 shows an example of the scattered spectrum (the dotted curve) for $N_{H} = 2 \times 10^{23}$ cm$^{-2}$ and $\Omega_o \approx 3\Omega$. We see that although this component contributes only weakly to the total continuum it accounts entirely for the Fe K line. We note that the scattered component does not have the shape characteristic to Compton reflection (with a fast increase of its relative contribution around 10 keV). Thus, the weak Compton reflection still present in the X-ray spectra of BLRGs cannot be explained by scattering in the surrounding optically-thin matter (see Section below).

We note that the surrounding medium will be, most likely, partly photo-ionized. For an ionizing luminosity typical for a BLRG in our sample, $L_{ion} \sim 5 \times 10^{44}$ erg s$^{-1}$, and a distance between the nucleus and the medium with $N_{H} \sim 2 \times 10^{23}$ cm$^{-2}$ of 5 pc, the ionization parameter (see Section 3) will be $\xi \sim 100$. Therefore, we assumed $\xi = 100$ in the illustrative example in Figure 13. At a typical medium temperature of $10^4$ K, the dominant Fe ion is found to be Fe XV, implying that resonant absorption of the line is negligible. We note that a range of ionization states in the line-producing medium will give rise to some broadening of the line.

A possible complication in the scenario with production of Fe K photons outside of the line of sight can be due to beaming of the primary radiation (e.g., Awaki et al. 1991). Beaming is expected in jet emission, and radio jets are present in most of the sources in our sample. Such beaming will relax the constraint on $(\Omega_o/4\pi)\tau_{o}$ discussed above. For example, we could explain the line in 3C 111 seen by Ginga as due to fluorescence in a medium with the observed $N_{H}$ ($\sim 2 \times 10^{22}$ cm$^{-2}$) if the irradiating flux is enhanced by a factor of $\sim 100$ in a cone with the opening angle of $15^\circ$.

Summarizing, we find that the simplest explanation of the Fe K line observed in BLRGs is a distant torus with $N_{H} \sim 2 \times 10^{23}$ cm$^{-2}$ covering a large solid angle as seen from the nucleus. More complex scenarios are, however, also compatible with the data.

7.2 The origin of the Compton reflection

A possible explanation of the apparent small solid angle of a Thomson-thick reflector, $\Omega \ll 2\pi$, is the primary emission originating in the vicinity of an accretion disk but collimated away from the disk. Collimation is expected in radio-loud AGNs, e.g., the $X_{\gamma}$ emission of blazars certainly originates in a jet pointing away from the source plane. For mild collimation, e.g., one due to a subrelativistic outflow, the observed reduction of Compton reflection by a factor of a few (with respect to an isotropic source above a disk) can be easily achieved. In this scenario, the bulk of the Fe K line does not originate in the reflection region, but rather in a remote torus (as argued in Section 7.1 above). Then we can explain both the approximate constancy with time of the line flux (from the remote torus) as well as constant relative weakness of the continuum reflection (from the disk close to the primary X-ray source). We note that some short time-scale variability of the line flux is predicted due to the disk-line contribution (with the expected $W_{Fe} \sim 30-50$ eV at the observed $\Omega$, e.g., GF91). Also, that disk-line component can be broad due to relativistic effects (e.g., Fabian et al. 1995).

Alternatively, the cold, reflecting, disk can be truncated at a large radius (in units of the Schwarzschild radius), due to, e.g., a disk instability. If the continuum source is located inside the truncation radius, the solid angle covered by the cold disk would be small. This scenario has been proposed to explain the weakness of Compton reflection in NGC 4151 (Zdziarski, Johnson & Magdziarz 1996).

The observed weak Compton reflection can also be possibly explained in the absence of a disk by reflection from the torus discussed in Section 7.1 above, provided $N_{H} \sim 10^{24}$ cm$^{-2}$ (Krolik, Madau & Życki 1994; Ghisellini, Haardt & Matt 1994). At this $N_{H}$ there will be already a signature of spectral hardening above $\sim 10$ keV, but the resulting reflection spectral component will be substantially weaker than
that from a medium with $N_H \gg 10^{24}$ cm$^{-2}$. This scenario requires some fine-tuning of $N_H$ and $\Omega_o$ but it is in principle possible. Note that in that case both the Fe K line and the reflection arise in the same region and a correlation on long time scales between $I_{Fe}$ and $\Omega$ would be present. The data presented here are insufficient to test for the presence of such correlation.

Finally, the weakness of Compton reflection could in principle be due to the dilution of the standard Seyfert-1 component with strong reflection by another component, e.g., from a comparatively low-luminosity blazar-like jet pointing close to our line of sight. This, in principle, would be supported by the detection of superluminal expansion in the radio images (see Section 4). However, the X-ray data do not support such a picture. First, the observed large fluxes of the Kα line cannot be directly explained in this scenario. Second, we have found that the data above $\sim 2$ keV do not allow the presence of a substantial second continuum component. We have considered a continuum model consisting of a power law with a free spectral index plus a (radio-quiet) Seyfert-1-like continuum with fixed $\alpha = 0.95$ and $\Omega/2\pi = 0.52$, i.e., the average values obtained by NP94. The line strength was not tied to either component. We have found that such a 2-component model provides a fit to the average Ginga spectrum worse than the single power-law plus reflection model used throughout this paper. The best fit to the 1-keV normalization of the Seyfert-1 continuum is null, and its upper limit is 2 per cent of the power-law normalization (at 90 per cent confidence). Even the upper limit would imply the reflection component much weaker than the observed $\Omega/2\pi \sim 0.1-0.3$. Thus, Compton reflection with this $\Omega$ observed in BLRGs cannot be explained as due to dilution of the Seyfert-1-like X-ray spectrum by another spectral continuum. This conclusion is supported for 3C 309.3 by observations of a pattern of X-ray variability implying a single X-ray source (Leighly & O’Brien 1997).

### 7.3 The origin of the continuum and the high-energy break

As found in the Section 7.2 above, the intrinsic X-ray continuum of BLRGs are unlikely to be composed of two components, e.g., one from the nucleus and one from a jet. Thus, the X-ray continuum in a BLRG appears to originate predominantly in a single emission source. This region may be either similar to that present in radio-quiet Seyfert 1s, or be related to an X-ray jet, as in blazars. In any case, the observed continuum emission has to be much more isotropic than in blazars at least in 3C 309.3, as shown by a Compton reflection component clearly detected in that BLRG. An important diagnostic for the nature of the continua can also be provided by the high-energy spectral breaks observed in the spectra.

We found that the presence of high-energy breaks in the spectra of BLRGs is established based on: (i) the break in the simultaneous ASCA/OSSE spectrum of 3C 120, (ii) the breaks seen in the average spectra of BLRGs observed repeatedly by both Ginga and OSSE and by both EXOSAT and OSSE, and (iii) the average spectra of all BLRGs observed by OSSE being much softer than both the individual X-ray spectra and the average Ginga and EXOSAT spectra. Furthermore, a similar break is clearly seen in Cen A (Kinzer et al. 1995), a narrow-line object considered to differ from BLRGs mostly by orientation (e.g., Antonucci 1993). The spectra are seen to break above $\sim 100$ keV, which is similar to the breaks seen in radio-quiet Seyfert 1s (Z95; Gondok et al. 1996; Zdziarski et al. 1996, 1997).

We note that models with an e-folded power law provide worse spectral fits to the average X-ray spectra than the broken power law model (Section 5.3), there are no available simultaneous X-ray observations with statistics sufficient to distinguish between different shapes in soft $\gamma$-rays of individual spectra. A spherical thermal Comptonization model of Poutanen & Svensson (1996) including Compton reflection fitted to the average Ginga/average OSSE spectrum yields the electron temperature of $kT_e \approx 110$ keV and the optical depth of $\tau \approx 1.3$ at the best fit, although the fit is worse than that with the broken power-law model (without reflection, Table 11), $\Delta \chi^2 = 3.4$. A similar thermal Comptonization model fits well the X-ray to soft $\gamma$-ray spectra of radio-quiet Seyfert 1s (e.g., Zdziarski et al. 1997). That model can also explain the anti-correlation between the X-ray slope and the ratio between the X-ray to UV fluxes observed in 3C 120 (Walter & Courvoisier 1992). Thus, thermal Comptonization remains a possible explanation of the $\gamma_\text{X}$ continua of BLRGs.

The relative hardness of the X-ray spectra in BLRGs with respect to radio-quiet Seyfert 1s can be related to the thermal Comptonization model to the relative weakness of Compton reflection in BLRGs. This can be explained as follows. In this model, the soft (UV/soft X-rays) seed photons are repeatedly upscattered by a hot plasma cloud to the hard X-ray/soft $\gamma$-ray range. In the case of radio-quiet Seyfert, the seed photons are from internal dissipation in an accretion disk as well as from reprocession of the incident X-ray photons (e.g., Haardt & Maraschi 1993). On the other hand, the seed photon field produced from reprocession is weak in BLRGs, as inferred from the weakness of the reflected component. The energy density of the seed photons in the plasma frame can be further Doppler-reduced if there is a sub-relativistic outflow of the plasma (see Section 7.2). From energy balance, the reduced supply of seed photons leads to reduced cooling and, consequently, to a hardening of the Comptonized X-ray spectrum (e.g., Poutanen & Svensson 1996). Physically, it can be realized, e.g., if the continuum source forms an inner hot accretion disk thermally Comptonizing cold radiation from the outer disk and cold clouds within the hot flow, and the reflection of the continuum is from the outer cold disk (see, e.g., Zdziarski 1998).

On the other hand, the X-ray and soft $\gamma$-ray spectra of BLRGs can be due to emission of nonthermal electrons. This possibility is hinted at by the apparent power-law shape (with no spectral curvature required) of the average OSSE spectrum of BLRGs (Section 5.3). Furthermore, the radio emission of BLRGs, and certainly that arising in the milliarcsecond region, is nonthermal. The X-ray spectral slopes of blazars, which emission is certainly nonthermal, are similar to those found in BLRGs. Also, the blazar spectra universally show a high-energy spectral break, which energy, however, falls in the MeV range. The nature of the break is not understood yet (e.g., Sikora et al. 1997), but it is generally agreed upon that their jets show Lorentz factors $\sim 10$; see Dondi & Ghisellini (1996). If the plasma in BLRGs propa-
8 CONCLUSIONS

The data presented here allow the first systematic comparison of the X-γ properties of BLRGs with their radio-quiet counterparts, Seyfert 1s. Our main conclusions are as follows.

1. The intrinsic (i.e., both absorption and reflection-corrected) X-ray continua of BLRGs are harder on average than those of (radio-quiet) Seyfert 1s. The Ginga data presented here give the average $\alpha = 0.67$ with a dispersion of 0.18, compared to the average $\alpha = 0.95$ with a dispersion of 0.15 in all Seyfert 1s (NP94). Also, the relative strength of Compton-reflected continuum in BLRGs corresponds to the reflector solid angle of $\leq 2\pi$ whereas the Seyfert-1 data yield significantly larger solid angles, on average of $\sim (0.5-0.7) \times 2\pi$ (NP94). The ASCA and EXOSAT data on BLRGs presented here are fully compatible with the data from Ginga.

2. The flux in the Fe K line in BLRGs is in most cases stronger than that expected from the observed weak Compton reflection. The corresponding average line equivalent width is $\sim 100$ eV. With a possible exception of 3C 120, the ASCA data are compatible with the Fe K line being unresolved. The line flux remains approximately constant in time in spite of the variable continuum in observations of individual objects spanning several years.

3. The simplest model of the origin of the Fe K flux is irradiation by the central X-ray source of a distant torus with $N_H \gtrsim 10^{23}$ cm$^{-2}$. The torus is away from the direct line of sight in the objects in our sample except for 3C 445, in which X-ray absorption by such a column density is directly observed.

4. The data show a high-energy spectral break at $\sim 100$ keV, which resembles that seen in radio-quiet Seyferts. The break can be explained by either thermal Comptonization or by nonthermal models, with the latter marginally favoured by the available data.

5. The main X-γ spectral properties of BLRGs: the hardness of the X-ray power law, weak reflection, and a high energy break above 100 keV, are also observed in the bright narrow-line radio galaxy, Cen A, which would be a BLRG viewed through the obscuring torus in the framework of the unified AGN model.

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