THE AVERAGE X-RAY/GAMMA-RAY SPECTRA OF SEYFERT GALAXIES FROM GINGA AND OSSE AND THE ORIGIN OF THE COSMIC X-RAY BACKGROUND

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ABSTRACT

We have obtained the first average 2–500 keV spectra of Seyfert galaxies, using the data from *Ginga* and *GRO* OSSE. Our sample contains 3 classes of objects with markedly different spectra: radio-quiet Seyfert 1s and 2s, and radio-loud Seyfert 1s. The average radio-quiet Seyfert 1 spectrum is well-fitted by a power law continuum with the energy spectral index $\alpha \approx 0.9$, a Compton reflection component corresponding to a $\sim 2\pi$ covering solid angle, and ionized absorption. There is a high-energy cutoff in the incident power law continuum: the e-folding energy is $E_c \approx 0.6^{+0.8}_{-0.3}$ MeV. The simplest model that describes this spectrum is Comptonization in a relativistic optically-thin thermal corona above the surface of an accretion disk. Radio-quiet Seyfert 2s show strong neutral absorption, and there is an indication that their X–ray power laws are intrinsically harder, although the Seyfert 1 spectrum with $\alpha = 0.9$ and strong reflection cannot be ruled out by the data. Finally, the radio-loud Seyfert spectrum has $\alpha \approx 0.7$, moderate neutral absorption, $E_c = 0.4^{+0.7}_{-0.2}$ MeV, and no or little Compton reflection. This is incompatible with the radio-quiet Seyfert 1 spectrum, and probably indicating that the X–rays are beamed away from the accretion disk in these objects.

The average spectra of Seyferts integrated over redshift with a power law evolution can explain the hard X-ray spectrum of the cosmic background. The hump at ~ 30 keV in that spectrum is due to the dominant contribution of Seyfert 2s.

Subject headings: Galaxies: Seyfert — X-rays: galaxies — diffuse radiation — gamma-rays: observations

1. INTRODUCTION

A major result of *GRO* has been a discovery that the soft γ-ray spectra of Seyferts (Sy) are significantly softer on average than the X-ray spectra; $\alpha_\gamma \simeq 1.2$ (Johnson et al. 1994 [J94]), compared to $\alpha_X \simeq 0.7$ (e.g., Turner & Pounds 1989), where $F_E \propto E^{-\alpha}$. Here we study the average Sy X-γ spectra observed by both *Ginga* and OSSE. We have used a sample of 9 Sy galaxies detected in 30 *Ginga* and 17 OSSE observations (Nandra & Pounds 1994 [NP94]; Smith & Done 1995; Awaki et al. 1991a, b; J94). The sample consists of 4 radio-quiet (RQ) Sy 1s (MCG –6-30-15 [4, 2], Mrk 509 [4, 2], NGC 3783 [1, 1], NGC 5548 [14, 3]), 3 RQ Sy 2s (MCG –5-23-16 [2, 2], NGC 4507 [1, 2], NGC 7582 [1, 2]), and 2 radio-loud (RL) Sy 1s (3C 111 [1, 1], 3C 390.3 [2, 2]), where the numbers in brackets give the number of *Ginga* and OSSE observations, respectively. The OSSE data is a subsample of 26 observations of 15 Seyferts for which the average spectrum (OSSE 15) was presented in J94 except for NGC 4507 added now (Bassani et al. 1994). The strongest OSSE detections of Seyferts (Cen A, NGC 4151, IC 4329A, NGC 4388) were excluded so that single sources would not significantly bias our results. The counts for individual observations were added with the weights corresponding to the length of time of each observation. The OSSE and *Ginga* spectra are not simultaneous, which may lead to some uncertainty of their relative normalizations. However, those normalizations are in qualitative agreement with the comparison of Sy fluxes from *EXOSAT* and OSSE in J94.

2. THE SPECTRA

We have found that although the average γ-ray spectra of RQ and RL Sy 1s, and RQ Sy 2s appear similar to each other (within the limited count numbers), the average X-ray spectra of different types are distinctly different. Therefore, we present the average spectra for each type separately.

We used the 2–30 keV *Ginga* channels except for the RL sample, where we used the 2–17 keV data only due to large background-subtraction errors above 17 keV. We have applied a 0.5% systematic error correction to the co-added *Ginga* data to allow for residual calibration uncertainties (which are negligible for OSSE compared to statistical errors).

2.1. Radio-Quiet Sy 1s

As found by Pounds et al. (1990) and NP94, X-ray spectra of RQ Sy 1s are well-fitted by power laws with $\alpha \simeq 0.9$–1 and a component due to Compton reflection (Lightman & White 1988) of the power law photons from cold matter covering a $\sim 2\pi$ solid angle which also contains a fluorescence Fe Kα line around 6.4 keV (e.g., George & Fabian 1991 [GF91]; Matt et al. 1991); these spectra are then absorbed by an external ionized medium.

In our modeling of Compton reflection, we used the spectrum averaged over the 2π angle of outgoing photons (White et al. 1988) rather than that seen face-on (which was used by NP94). Below ~ 10 keV, the latter equals the former times 1.32 (Ghisellini et al. 1994). For absorption in the reflecting medium, we used the neutral absorption cross sections of Bałucińska-Church & McCammon (1992) with the elemental abundances of Morrison & McCammon (1983). However, we assumed H and He to be fully ionized, as expected in Sy accretion disks (Ross & Fabian 1993). For an isotropic source the amount of reflection averaged over a slab subtending a 2π solid angle is defined as $R = 1$. The Fe abundance can differ from that measured locally (e.g., Yaqoob et al. 1993; NP94), so in some models we allowed $A_{\rm Fe}$ (defined relative to the abundance of Morrison & McCammon 1983) to vary. The Fe Kα line is modeled as a Gaussian line with normalization proportional to the amount of reflection. The equivalent width, EW, of the line with respect to the reflected continuum alone remains poorly determined theoretically; its estimates vary from ~ 0.7 to ~ 1.4 keV for $\alpha = 0.9$ and $A_{\rm Fe} = 1$ (Życki & Czerny 1994; GF91). Here we adopted a middle value of $EW = 1\,{\rm keV} \times R(A_{\rm Fe})^{1/2}$ (see Fig. 17 in GF91), which corresponds to $EW \simeq 90$ eV (at $R = A_{\rm Fe} = 1$) with respect to the power law plus reflection continuum.

Ionized absorption is found to be required for our data (see also NP94). It is modeled using a one-zone approximation with the ionization state (at the ionization parameter, ξ) and the opacities computed as described in Done et al. (1992), but with elemental abundances as for reflection (see above). The temperature of the medium is kept at 5×10^4 K (see Krolik & Kallman 1984).

The average X-γ spectrum of our sample is indeed well described by ionized absorption, a power law ($\alpha \simeq 0.9$), and reflection up to ~ 100 keV (Fig. 1). However, there is evidence for a break in the incident spectrum at higher energies. Describing this by an exponential cutoff in the power law spectrum, $E^{-\alpha}\exp(-E/E_c)$, gives an excellent fit to the data, see Table 1. The reflection normalization ($R \simeq 1.3^{+0.3}_{-0.2}$) equals that expected for the face-on disk geometry, and $EW \simeq 110$ eV. ($R \gtrsim 1.3$ are possible if there is also reflection from a torus, Ghisellini et al. 1994; Krolik et al. 1994.) If the theoretical EW with respect to the reflected continuum is increased to 1.4 keV, as obtained by GF91, then $R = 1.2^{+0.3}_{-0.2}$, with χ^2 larger by 4. Reflection is *required* for our RQ Sy 1 sample, and it causes a spectral upturn above 10 keV, as clearly seen in Fig. 1. Partial covering by Thompson thick material can also fit the continuum but fails to account for the Fe line (Zdziarski et al. 1994). We kept $A_{\rm Fe} = 1$ in the fits; the best fit value (0.82) is very close to unity.

There is a high-energy break in the incident spectrum (Table 1), with $E_c \gg 100$ keV in spite of the total spectrum peaking at $\lesssim 100$ keV. This is due to the presence of the reflection component, which causes the total spectrum in the ~ 10–30 keV and ~ 50–300 keV ranges to be harder and softer, respectively, than the incident spectrum. Thus, the presence of reflection is a major cause of the average RQ Sy 1 spectrum in the OSSE range being much softer than a simple power-law description of the spectrum in the *Ginga* range.

Similar parameters to those in Table 1 have been obtained by us for the X-ray spectra of individual AGNs in the sample. Also, we have fitted the average spectrum without NGC 5548, which 14 observations dominate the *Ginga* sample. We have obtained parameters similar to those in Table 1 ($R = 1.3^{+0.4}_{-0.2}$, $\alpha = 1.00^{+0.04}_{-0.02}$, $E_c = 550^{+1730}_{-270}$ keV), showing that the presence of this object does not introduce a significant bias in our average spectrum.

2.2. Radio-Quiet Sy 2s

We see in Fig. 1 that the X-ray spectrum of Sy 2s is much harder than that of Sy 1s. One cause of this is obscuration by neutral matter: NGC 4507 and NGC 7582 have $N_{\rm H} \sim 10^{23.5}$ cm^{-2} and MCG –5-23-16, $N_{\rm H} \sim 10^{22}$cm^{-2}. To account for this disparity of $N_{\rm H}$, we model absorption by the product of complete and partial covering (with the covering factor f_c and the column density $N_{\rm H}^p$), which can also account for a possible component scattered by optically thin hot electrons above an obscuring torus. Furthermore, the X-ray spectrum of NGC 7582 contains some emission from an optically thin plasma in the Sersic 159 cluster, which we included in the model for the co-added spectrum using the parameters obtained by fitting the X-ray spectrum of that AGN alone.

The spectrum contains an Fe line stronger than that expected from reflection alone, which implies a component from the absorbing medium (e.g., Inoue 1989). Thus, we allowed for a free normalization of the line. For $A_{\rm Fe} = 1$, $\alpha = 0.67$, $R = 1.3$ (Table 1), and $EW \approx 300$ eV. The power law component is harder than that of Sy 1s and this difference is accentuated if we allow for variable $A_{\rm Fe}$; we obtain $A_{\rm Fe} = 2.3$, $\alpha = 0.4$, $R = 0$, and $\Delta\chi^2 = -4$, where Δ denotes change with respect to Table 1 (an equally good fit is obtained with $A_{\rm Fe} = 1$ from an optically thick Compton continuum: see §3). If we impose the same intrinsic spectral form as for Sy 1s ($\alpha = 0.9$, $R = 1.3$, $A_{\rm Fe} = 1$, $E_c = 560$ keV), $\Delta\chi^2 = 7$: a worse fit but within the 90% confidence contour for the 3 correlated parameters α, R and E_c. However, given that the unification schemes imply that Sy 2s are seen at higher inclination angles than Sy 1s, we might expect less reflection in the Sy 2s. Repeating the above fit with $R = 1$ gives $\Delta\chi^2 = 10$, over 2σ away from the best fit Sy 2 spectrum.

We note that the X-ray spectra of individual objects in our sample as well as the X-ray spectra of other Sy 2s observed by *Ginga* (Smith & Done 1995) are better described by an intrinsic power law that is significantly harder and with less reflection than that for Sy 1s. The hypothesis that $\langle\alpha\rangle \simeq 0.9$ in all Sy 2s in general can be ruled out (Smith & Done 1995). If the Sy 2s in this sample also have values of α lower than those for Sy 1s, this implies a lower E_c in order to account for the similar γ-ray spectra in both samples; in the model with $\alpha = 0.4$, $E_c \simeq 100$ keV. The co-added Sy 2 spectrum then looks very similar to that of NGC 4151, a Sy 1.5 (similar to Sy 2s, Ayani & Maehara 1991), as observed by OSSE and *Ginga* (Zdziarski et al. 1993; Maisack et al. 1993). In that object, the intrinsic power law varies from $\alpha = 0.3$ to 0.7 and $R \ll 1$ (Yaqoob et al. 1993), which is consistent with the spectral fits for our Sy 2 sample.

Thus, there are indications that the intrinsic X–ray spectra of Sy 2s are in general substantially harder than those of Sy 1s (which imply a lower energy γ-ray cutoff). However, this intrinsic difference in spectrum between Sy 1 and 2 objects cannot be explained by the simplest version of the unified AGN theory (Antonucci 1993). Another prediction of that theory (in addition to absorption of the intrinsic spectrum) is an unobscured spectral component due to reflection from the inner side of the torus directly seen for some viewing angles (Ghisellini et al. 1994; Reynolds et al. 1994). We have tested that model and found that it is strongly ruled for our sample if $\alpha = 0.9$; if α is not fixed, an acceptable model has $\alpha \simeq 0.2$–0.3 and an unobscured reflection component with $R = 0.4^{+0.5}_{-0.4}$.

2.3. Radio-Loud Sy 1s

We find here $\alpha \simeq 0.7$, $R = 0^{+0.5}$, $EW = 70$ eV, and neutral absorption. There is no visible spectral upturn above 10 keV characteristic for reflection (Fig. 1). The spectrum is significantly different from that of RQ Sy 1s; $\alpha = 0.9$ and $R = 1.3$ are strongly ruled out ($\chi^2 = 505$). The γ-ray spectrum is poorly determined due to a low count number.

2.4. All Seyferts

The co-added spectrum of all 9 Seyferts in our sample is presented in Fig. 1. The X-ray spectrum is relatively similar to that of RQ Sy 1s, as they have the softest X-ray spectra and dominate the spectrum at the lowest energies. Thus, we used the same model as for RQ Sy 1s (see Table 1; $EW = 110$ eV). Note that since the sample contains objects with 3 distinct spectral classes, this model should be treated as a phenomenological description of the average spectrum rather than a representation of the average parameters of Sy AGNs.

As the γ-ray count number is much higher than that for the subsamples, E_c is relatively tightly constrained, to 390^{+190}_{-100} keV. Note that E_c depends sensitively on α and R, which is determined by the *Ginga* spectrum. We have also repeated the fit using the OSSE 15 spectrum, which is consistent with the same spectral form but it has more counts. We have obtained now $E_c = 320^{+110}_{-70}$ keV. This E_c is significantly higher than the e-folding energy obtained by fitting the OSSE 15 spectrum alone (J94). The reasons for the discrepancy are, first, the X-ray power law spectrum being much softer than that obtained by J94 by fitting the OSSE energy range alone, and, second, the presence of a reflection component.

3. PHYSICAL PROCESSES IN SEYFERTS

The spectrum of our sample of RQ Sy 1s is very similar to that of IC 4329A, the second brightest γ-ray RQ Sy. Its spectrum has a similar reflection component and $E_c \lesssim 1$ MeV (Madejski et al. 1995). The physical processes that can lead to such a spectrum are studied in Zdziarski et al. (1994), where the spectrum is modelled by Comptonization of UV photons in an optically thin, relativistic, thermal plasma ($\tau_{\rm T} \sim 0.1$, $kT \sim 250$ keV), which may form a corona above the surface of an optically thick accretion disk. Optically thick Comptonization (Sunyaev & Titarchuk 1980) is ruled out. Most of the dissipation of the gravitational energy occurs probably in the corona (Haardt & Maraschi 1993; Svensson & Zdziarski 1994). On the other hand, nonthermal models with most of the power injected in electrons with low Lorentz factors are also possible.

Our Sy 2 spectrum is marginally compatible with that of Sy 1s with additional strong obscuration. If this is indeed the case, the same physical processes are likely to operate. On the other hand, the intrinsic Sy 2 spectrum may be harder, similar to that of NGC 4151. Similarly to that object (Zdziarski et al. 1993; Maisack et al. 1993) we obtained a very good fit ($\chi^2 = 59$) for optically thick thermal Comptonization (Sunyaev & Titarchuk 1980), with $\tau = 2.9^{+1.7}_{-0.9}$ and $kT = 39^{+28}_{-9}$ keV (at fixed $R = 0$ and $A_{\rm Fe} = 1$).

The emission of RL Seyferts is likely to be related to nonthermal Compton scattering in jets seen at a large angle. This emission may originate in the base of a jet with a low bulk Lorentz factor, which results in less collimation of radiation than in blazars. Alternatively, the strongly collimated jet emission may be scattered towards our line of sight by a cloud, as proposed for Cen A, a RL Sy 2 (Skibo et al. 1994). In either case, the lack or weakness of reflection is explained by the emission being beamed away from the disk.

4. THE CONTRIBUTION TO THE X-RAY BACKGROUND

We have used the best-fit models (Table 1) for the 3 classes of Seyferts to estimate their contribution to the cosmic X-ray background (XRB). We assume a power law evolution of the comoving volume emissivity, $\propto (1+z)^\beta$, up to some $z_{\rm max}$. Fig. 2 shows an example of a model with $\Omega = 0$, $\beta = 2$, $z_{\rm max} = 3$, and the local volume emissivity in the 2–10 keV range of $\langle nL \rangle_0 = 2.9$, 4.8, and 0.77 $\times 10^{38} h$ ergs s^{-1} Mpc^{-3} for RQ Sy 1s, Sy 2s, and RL Sy 1s, respectively [$h \equiv H_0/(100$ km s^{-1} Mpc$^{-1})$]. The total $\langle nL \rangle_0$ approximately equals the estimates for both all local sources (Lahav et al. 1993) and local AGNs (Piccinotti et al. 1982). The relative normalizations of the 3 classes of sources correspond to the Sy 2 density about ~ 5 times higher than that of Sy 1s (e.g., Osterbrock & Shaw 1988), and the RL Sy 1 density of about 10% of that of RQ objects (Della Ceca et al. 1994). One sees that the fit is excellent although no minimization of χ^2 has been done. The characteristic peak in the XRB spectrum at ~ 30 keV is explained by the contribution from Sy 2s dominant in this energy range. One sees that Sy 1s alone are not capable to explain the XRB, as noted before by Zdziarski et al. (1994). The dominant contribution of Sy 2s has been proposed before by, e.g., Madau et al. (1993), and Matt & Fabian (1994). Here, we confirm their predictions using for the first time the actually observed spectral parameters of AGNs.

5. CONCLUSIONS

The average 2–500 keV spectrum of RQ Sy 1s is well described by an intrinsic power law spectrum with $\alpha \approx 0.9$ with an exponential cutoff energy of order of several hundred keV and a Compton reflection component. This cutoff energy is *not* ~ 40 keV, as obtained earlier based on limited-band γ-ray spectra (e.g., J94, Bassani et al. 94). RQ Sy 2s may be intrinsically harder than Sy 1s although the same underlying spectrum as in Sy 1s cannot be ruled out on the basis of our limited sample. The average spectrum of RL Sy 1s, with an $\alpha \simeq 0.7$ power law and no or little reflection, is *not* compatible with that of RQ objects. The contributions from the 3 classes objects fits well the XRB, with Sy 2s dominating near the XRB peak at 30 keV.

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Fig. 1.— The composite spectra of Sy AGNs observed by both *Ginga* and OSSE (crosses; adjacent bins have been added to achieve $\geq 2\sigma$ significance). The upper limits are 2-σ. The dashed curves represent absorbed power law spectra with exponential cutoffs. The dotted curves represent the reflection and/or Fe line contribution. The solid curves give the sum. The dot-dashed curve for RQ Sy 2s gives the model spectrum including a contribution from an optically thin plasma emission (Raymond & Smith 1976) at $kT = 2.1$ keV and the abundance of 0.2 from the Sersic 159 cluster in NGC 7582.

Fig. 2.— The contributions of Sy 1 and 2 galaxies to the cosmic X-ray and γ-ray background. Dotted, dashed, and solid error contours are from *ROSAT* (Hasinger 1992); *ASCA* (Gendreau et al. 1994), and *SAS-2* (Fichtel et al. 1978); circles are a compilation of best results from various experiments by Gruber (1992); and the shaded region is the systematic error contour for the *Apollo* results, with the middle dot-dashed curve being the best estimate of the spectrum (Trombka et al. 1977). The solid curve is the sum contribution from RQ Sy 1s (dots), 2s (dashes), and RL Sy 1s (dot-dashed curve). See §4 for the evolution parameters; the spectral parameters are as found for our average spectra (see §2).