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X-rays and gamma-rays from radio-quiet Seyfert 1's and Cyg X-1

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Abstract. We review broad-band X-ray/γ-ray spectra of radio-quiet Seyfert 1 galaxies as well as their theoretical implications. Average Seyfert 1's have intrinsic power-law spectra with $\alpha \sim 0.9$ with a break at ~ 0.3–1 MeV, and a superimposed Compton reflection component from cold matter covering a ~ 1–2π solid angle as seen by the power-law source. The reflection component is responsible for a hardening of the spectrum in the ~ 10–30 keV range and a softening at ~ 30–200 keV. A rather similar spectrum is seen in the hard state of Cyg X-1, a black-hole binary source. Simultaneous *Ginga*/OSSE observations show $\alpha \simeq 0.6 - -0.7$, a strong Compton reflection component, and a high-energy cutoff at ~ 200 keV. The simplest model for the intrinsic spectra is thermal Comptonization of soft seed photons. The scattering medium is relativistic ($kT \sim 200$ keV or more), optically thin and probably forms a corona above a cold accretion disk. However, some nonthermal models can also fit the data. On the other hand, the X-ray spectra of some radio-quiet Seyferts appear distinctly different from that above. NGC 4151 has a variable $\alpha \sim 0.2$–0.7, no Compton reflection, and a high-energy break corresponding to $kT \sim 50$ keV of an optically-thick Comptonizing plasma. There is no Compton reflection seen in the spectra, which implies that the hot source is not a disk corona.

The spectra of Seyfert 1's alone cannot account for the hard X-ray cosmic background. However, the X-ray/γ-ray background can be explained by the sum of contributions from evolved Seyfert 1's, Seyfert 2's, blazars, and, possibly, supernovae type 1a.

Key words: galaxies: Seyfert – X-rays: galaxies – gamma-rays: observations – diffuse radiation – accretion, accretion disks – radiation mechanisms: non-thermal

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1. Introduction

The origin of X-rays and γ-rays (hereafter X-γ) from Seyfert galaxies and Galactic black-hole candidates remain major unresolved problems of high energy astrophysics. A chance to solve it has been provided by soft γ-ray observations of those objects by the OSSE detector aboard *GRO*. In some cases, those spectra can be combined with X-ray spectra obtained by other instruments (Madejski et al. 1995, hereafter M95; Zdziarski et al. 1995, hereafter Z95; Bassani et al. 1995; Zdziarski at al. 1996, hereafter Z96; Gierliński et al. 1996; Gondek et al. 1996). The resulting broad-band spectra have allowed a confrontation of theoretical models with observations unprecedented before the launch of *GRO*.

In this paper, we review some of the recent observational and theoretical results on X-γ radiation from radio-quiet Seyfert 1's as well as their contribution to the cosmic X-ray background (hereafter XRB). We show a remarkable similarity between the spectra of Seyfert 1's and of the black-hole candidate Cyg X-1, and discuss spectral differences between Seyfert 1's and a Syfert 1.5 galaxy NGC 4151. Sections 2, 3, and 4 present observational results on an average Seyfert 1, Cyg X-1, and NGC 4151 X-γ spectra, respectively. In section 5 we discuss radiative processes in above objects. Section 6 presents contribution of various classes of AGNs to the cosmic X-γ background.

2. Radio-Quiet Seyfert 1's

The X-ray spectra of radio-quiet Seyfert 1's (Pounds et al. 1990; Nandra & Pounds 1994) have a power-law component with the energy spectral index of $\alpha \simeq 0.9$–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 (presumably a cold accretion disk). This two-component spectrum is then absorbed by an external, partially ionized medium. The reflection component forms a broad hump with the maximum around 30 keV on top of the flat (in EF_E) power law. Thus, the composite spectrum is harder than the incident power law below $\sim$ 30 keV and softer at higher energies. The reflection component also contains a fluorescent Fe Kα line around 6.4 keV with the equivalent width of $\sim$ 100–200 eV (e.g., George & Fabian 1991; Matt at al. 1991). Above $\sim$ 200 keV, there is evidence for a break in the incident power law (M95; Z95) which can be modeled by an exponential cutoff with an e-folding energy, $E_c \sim 0.3$–1 MeV.

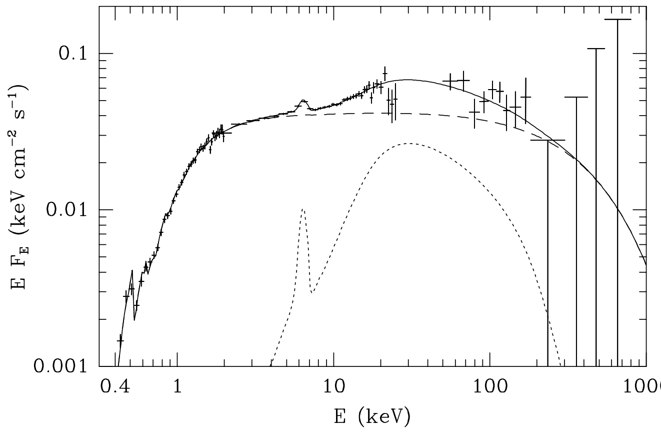

Fig. 1. The broad-band *ROSAT*/*Ginga*/OSSE spectrum of IC 4329A. The data are the same as those of model D in M95 and the fit is from Magdziarz & Zdziarski (1995). The upper limits here and in figures below are 2-σ. The dashed curve represents the best-fit absorbed power law with an exponential cutoff. The dotted curve represents the absorbed reflected component (the reflected spectrum includes a fluorescent Fe Kα line). The solid curve is the sum.

The Seyfert 1 brightest at 2 keV, IC 4329A, has the X-γ spectrum of this form (M95), as shown in Figure 1. The energy spectral index is $0.9 \lesssim \alpha \lesssim 1$. The e-folding energy is constrained to 0.25 MeV $\lesssim E_c \lesssim$ 1 MeV. We see in Figure 1 that most of the relative steepness of the γ-ray spectrum with respect to the X-ray spectrum is due to Compton reflection. The absorbing medium is partly ionized whereas the reflecting medium is close to neutral (Zdziarski et al. 1994, hereafter Z94). The hard flux irradiating the reflecting medium is $R \sim 0.7$ of that emitted outward assuming the disk viewing angle of 30^o (Magdziarz & Zdziarski 1995), which angle is thought to be characteristic for Seyfert 1's (e.g., Antonucci 1993). Spectra very similar to that of IC 4329A have been obtained by Gondek et al. (1996) by co-adding spectra of radio-quiet Seyfert 1's repeatedly observed by both *Ginga* and OSSE and by *EXOSAT* and OSSE (Fig. 2). The spectral parameters of the average *Ginga*/OSSE spectrum (Fig. 2a) are $\alpha = 0.9^{+0.04}_{-0.04}$,

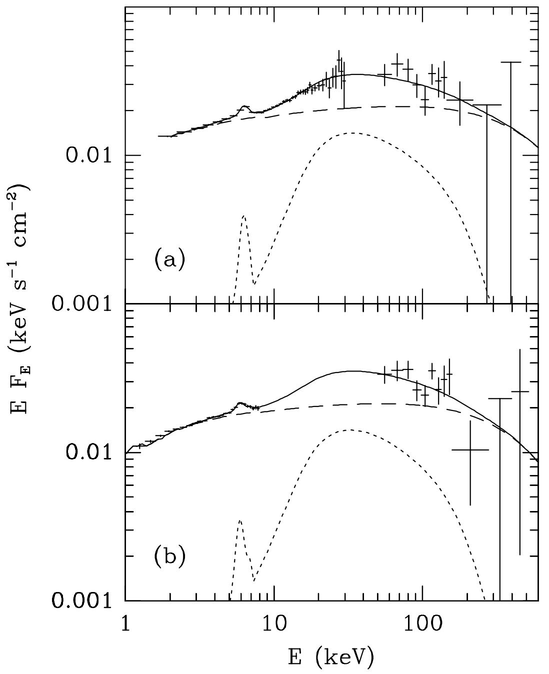

Fig. 2. The average spectra (*crosses*) of radio-quiet Seyfert 1 galaxies. *(a)* The *Ginga*/OSSE sample. *(b)* The *EXOSAT*/OSSE sample. The dashed curves represent power-law spectra with an exponential cutoff at high energy and bound-free absorption at low energy. The dotted curves represent Compton reflection including the Fe Kα line. The solid curves give the sum. Note the similarity of the spectra to that of IC 4329A (Fig. 1).

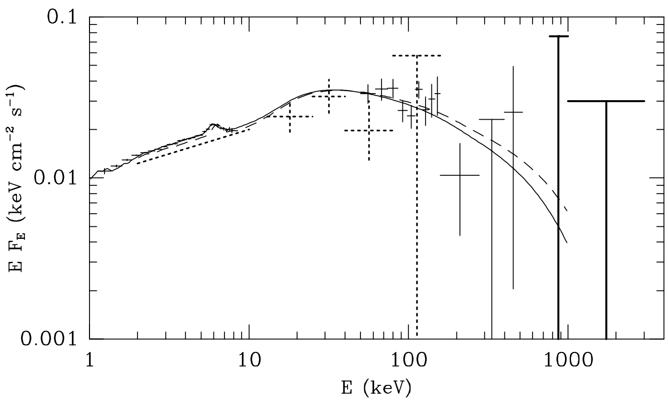

Fig. 3. Comparison of the average spectra for radio-quiet Seyfert 1's obtained with various instruments. The data points in solid thin line are from *EXOSAT* and OSSE. The solid and dashed curves are the best-fit models for the *EXOSAT*/OSSE and *Ginga*/OSSE samples, respectively. The dotted symbols are for *HEAO-1* A1 and A4. We see that there is an overall agreement between results from different instruments. The thick-line upper limits are for combined emission of all Seyfert galaxies observed by COMPTEL (Maisack et al. 1995).

$R = 0.7^{+0.1}_{-0.1}$, and $E_c = 0.6^{+1.0}_{-0.3}$ MeV, very similarly to IC 4329A. The average *EXOSAT*/OSSE spectrum (Fig. 2b) is almost identical to the *Ginga*/OSSE average, as shown in Fig. 3, which also demonstrates that both averages are consistent with the corresponding average for *HEAO-1* A1 and A4.

3. Cyg X-1

Cygnus X-1 is a binary system that consists of an O9.7 supergiant and a compact object which is believed to be a black hole. On June 6, 1991 Cyg X-1 was observed 4 times by *Ginga* and OSSE simultaneously (Gierliński et al. 1996). This provided a unique opportunity to see instantaneous, broad-band spectra of Cyg X-1, covering the energy range from 2 to 1000 keV. The spectra correspond to the highest γ-ray state observed by OSSE (Phlips et al. 1995).

We have initially fitted the joint spectra by exponentially cut-off power law with Compton reflection and a Gaussian line at 6.4 keV, as for radio-quiet Seyfert 1's. However, this model requires an addition of another component peaking around 200 keV, which we represented by exponentially cut-off ($E'_c \sim 70$ keV), hard ($\alpha' \lesssim -1$) power law. The fit requires a Compton reflection continuum component accompanied by a Fe Kα fluorescent line. The width of the line is consistent with theoretically expected $\sim$ 100 eV (George & Fabian 1991). Figure 4 shows the resulting fit for the first set from the simultaneous *Ginga*/OSSE observations. The best fit parameters are: the energy spectral index $\alpha = 0.62$, and $\alpha' = -1.23$; the *e*-folding energy, $E_c = 217$ keV, and $E'_c = 72$ keV; the covering factor of the reflector, $R = 0.38$.

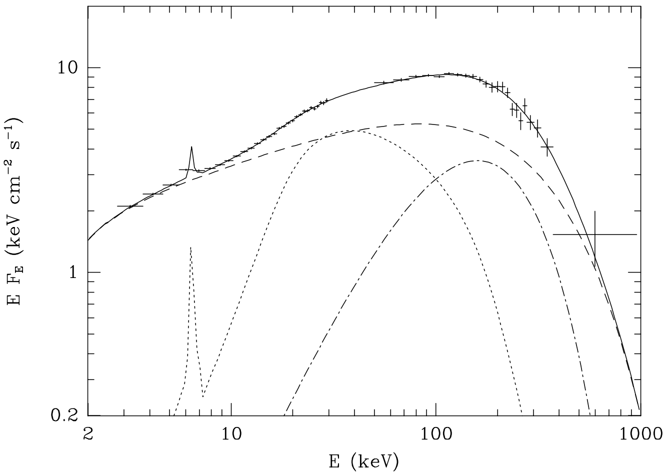

Fig. 4. The two-component model for the simultaneous *Ginga*/OSSE observation. The dashed curve represents the main, exponentially cut-off power-law component, the dotted curve – a disk reflection continuum, and the dash-dotted curve – the additional cut-off power-law component (cf. Sect. 3). Solid curve shows the sum.

The cutoff in the spectra appears above $\sim$ 150 keV, however its form is described neither by an exponentially cut-off power law nor by thermal Comptonization (treated relativistically). This effect can be due to a distribution of plasma temperature and optical depth. The additional component can be a manifestation of a strongly Comptonized, optically thick plasma. Then the main continuum component corresponds to an optically thin plasma at $kT \sim 150$ keV. Note that the spectral index of this component ($\alpha \sim 0.6$–0.7) is somewhat harder than the average spectral index in radio-quiet Seyfert 1's (cf. Sect. 2); however, the overall spectra of Cyg X-1 and Seyfert 1's look remarkably similar.

4. NGC 4151

NGC 4151 is the brightest Seyfert in soft γ-rays. It is a Seyfert galaxy classified as 1.5 (e.g., Ayani & Maehara 1991). It is not, however, a typical Seyfert 1 as far as its X-γ emission is concerned. Its 2–10 keV spectral index varies from $\alpha = 0.3$ to 0.7 (Yaqoob et al. 1993) rather than it equals 0.9. A reflection component is either absent or very weak (Yaqoob et al. 1993; Z96). Its spectrum looks similar to that of Seyfert 2's (Z95; Smith & Done 1995), which difference is often presumed to the effect of absorption by a Thomson-thick molecular torus seen close to edge-on (e.g., Antonucci 1993). However, the spectral difference between NGC 4151 and the average Seyfert 1's appears intrinsic rather than due to varying degree of absorption (e.g., Yaqoob et al. 1993).

The OSSE observations of NGC 4151 show a strong break in the spectrum near 100 keV (Maisack et al. 1993; Z96; Johnson et al. 1996). The sharpness of the break allowed to rule out models with most of the power supplied to the source in the form of nonthermal electrons (Zdziarski at al. 1993, hereafter Z93). The OSSE data alone are not able to distinguish between the spectra of NGC 4151 and of the average Seyfert 1's (Z96). This is because the fitting parameters are poorly determined for the average Seyfert 1 from the OSSE data.

On the other hand, the broad-band X-γ spectra can be well fitted by thermal Comptonization (Maisack et al. 1993; Z93; Z96) with the emitting plasma mildly relativistic and optically thick ($kT \sim 50$ keV, $\tau \sim 2$ from Z96). This stays in contradiction to the thermal plasma parameters fitted to the broad-band spectra of the average radio-quiet Seyfert 1's, which show the emitting plasma to be highly relativistic and optically thin (cf. Sect. 5). The spectral variability of NGC 4151 consists of varying X-ray power law pivoting at the spectral brake point of ~ 100 keV, however there is some evidence that this pattern occasionally breaks down (Z96). The solid curve in Figure 5 shows the best fit of the thermal Comptonization model (with plasma parameters of $kT = 53$ keV and $\tau = 1.7$ in spherical geometry) to the *ROSAT*/*Ginga*/OSSE spectrum in June–July 1991.

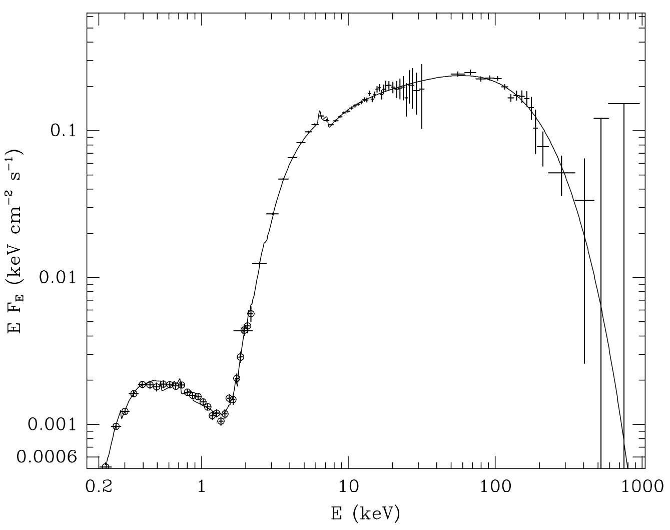

Fig. 5. The spectrum of NGC 4151 from *ROSAT*, *Ginga*, and OSSE observed contemporaneously in 1991 May 31–July 12 (Z96). The *ROSAT*data are marked with circles. The solid curve gives the best-fit thermal Comptonization spectrum including absorption by an intervening medium and a separate soft X-ray component.

5. Radiative Processes

Most models of X-rays and γ-rays from Seyferts assume that they originate from Compton upscattering by energetic electrons of some seed photons, presumably from the UV bump (e.g., Svensson 1994). The distribution of the energetic electrons can be either thermal (Shapiro et al. 1976; Katz 1976; Sunyaev & Titarchuk 1980) or nonthermal (Svensson 1987; Lightman & Zdziarski 1987 and references therein). This distinction gives rise to the two corresponding main classes of models, thermal and nonthermal.

Possible emission models for the X-γ spectrum of IC 4329A have been studied by Z94; that analysis applies to the average *Ginga*/OSSE spectrum of Seyfert 1's as well. They found that either thermal or nonthermal models can fit the data.

The simplest model that fits the data with virtually no free parameters is a hot, dissipative, thermal corona above the surface of an accretion disk. Most of the dissipation of the gravitational energy occurs in a surface layer of the disk (Haardt & Maraschi 1993; Svensson & Zdziarski 1994) rather than deep inside the disk. The heated surface layer forms a hot corona, whose electrons Compton upscatter soft photons radiated by the optically thick part of the disk. The soft photons are due to re-emission of a $\sim 50\%$ of the hard radiation of the corona directed downward. The soft photon temperature, T_s, depends weakly on the size and luminosity of the corona. The obtained range of T_s agrees with the observational constraint of $T_s \sim 10$ eV, i.e., the soft photons coming from the UV bump. The corona is in energy balance, which provides a relation between its temperature, T, and the Thomson optical depth, τ. Furthermore, $kT \sim E_c$, and the observed $\alpha = \alpha(T, \tau)$. The above relations form a closed system of equations with no free parameters. It turns out that the spectral parameters of Seyferts satisfy that system within the observational uncertainties. The parameter with the largest uncertainty is E_c. In the case of the spectrum of IC 4329A, $E_c = 400$ keV satisfies the model equations (Z94). This E_c corresponds to $\tau = 0.1$.

The constraints on the model can be weakened if some dissipation takes place also in the disk and/or not all soft photons irradiate the plasma cloud (i.e., the corona is patchy, Haardt et al. 1994). In the first case, higher E_c and smaller τ are possible, in the second, lower E_c and larger τ.

The observational lower limit of $E_c \gtrsim 200$ keV (for both IC 4329A and the average Seyfert 1), corresponds to $\tau \lesssim 0.5$, i.e., to optically *thin* plasmas (regardless of the applicability of the above dissipative corona model). Optically thick Comptonization (Sunyaev & Titarchuk 1980) is ruled out in Seyfert 1's. On the other hand, the NGC 4151 spectra show $E_c \sim 100$ keV, and optical thickness $\tau \sim 2$, i.e. mildly relativistic and optically thick Comptonization. The plasma appears to be photon starved in this case and energy balance rules out the homogenous corona. This favours rather the patchy corona models or implies that the hot source is not a disk corona at all, which is consistent with the lack of Compton reflection in the spectra (Zdziarski & Magdziarz 1996).

Regardless of the pair abundance, no pair annihilation feature is observable (Maciołek-Niedźwiecki et al. 1995).

On the other hand, it is also physically possible that only selected particles are accelerated to (or injected at) high energies (rather than all particles are uniformly heated). Z94 found that only nonthermal models in which most of the injection occurs at low Lorentz factors fit the IC 4329A data, which conclusion also holds for the average Seyfert 1 spectrum. In particular, models with a power-law elec-

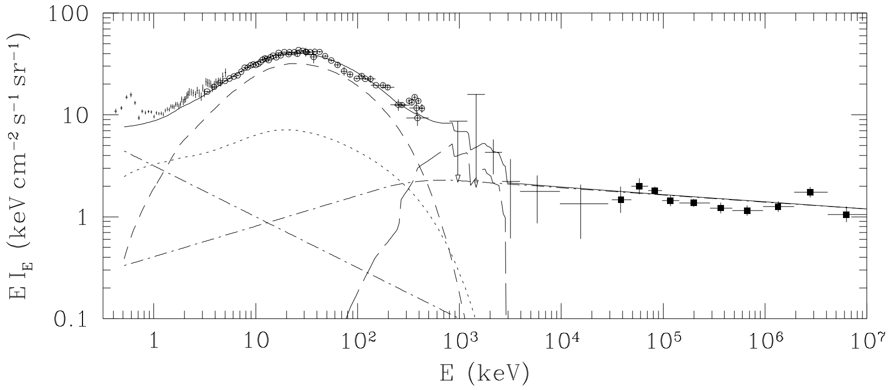

Fig. 6. Estimated contributions of various classes of AGNs to the cosmic X-ray/γ-ray background. Crosses in the 0.4–7 keV range are from ASCA (Gendreau 1995; including a Galactic contribution, dominant below 1 keV); circles (3–500 keV) are a compilation of best results from various experiments by Gruber (1992); the 1–30 MeV symbols are from COMPTEL (Kappadath et al. 1995), and the filled squares are from EGRET (Sreekumar et al. 1995). Dots and short dashes give the contributions from radio-quiet Seyfert 1's, and 2's, respectively, as estimated by Z95. A dot-dashed curve (dominating below 1 keV) gives a contribution from steep-X-ray spectrum quasars as estimated by Chen et al. (1995). Long dashes (peaking at 1 MeV) give an estimate of the contribution from supernovae type 1a (The et al. 1993). A dot-dashed curve gives the contribution from blazars, including MeV blazars, estimated using the results of Chiang et al. (1995). The solid curve is the sum.

tron injection with $\Gamma > 2$ [$N(\gamma) \propto \gamma^{-\Gamma}$] with $\gamma_{\min} \sim 5$ fit well IC 4329A. The power-law injection gives rise to a pair cascade (e.g., Lightman & Zdziarski 1987; Zdziarski et al. 1990). The produced pairs annihilate and give rise to a feature around 511 keV, which contains about 5% of the X-γ luminosity (within the data upper limits). Another possible nonthermal model considered by Z94 has a monoenergetic electron injection at $\gamma \sim 3$. In this case there is no pair production and the spectrum is formed by repeated Compton scatterings by the nonthermal electron distribution (Ghisellini et al. 1993).

6. The contribution to the X-ray/gamma-ray background

Z95 estimated the contribution of Seyfert 1's and 2's to the XRB using their obtained average spectra from *Ginga* and OSSE. Dashed and dotted curves in Figure 6 show their results for $\Omega = 0$ and the comoving volume emissivity $\propto (1+z)^2$ up to $z_{\max} = 3$. The local volume emissivities in the 2–10 keV range are $\langle nL \rangle_0 = 2.9$ and $4.8 \times 10^{38} h$ ergs $\mathrm{s^{-1}\ Mpc^{-3}}$ for radio-quiet Seyfert 1's and 2's, respectively [$h \equiv H_0/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$]. 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 normalization of the 2 classes of sources correspond to the Seyfert 2 density about ~ 5 times higher than that of Seyfert 1's (e.g., Osterbrock & Shaw 1988). We see that Seyfert 1s alone are not capable to explain the XRB, as noted before by Z94. The dominant contribution of Seyfert 2's to the hard X-ray background has been proposed before by, e.g., Madau at al. (1993, 1994), Matt & Fabian (1994), and Comastri et al. (1995).

Note that including such sources of the diffuse background as quasars, blazars, and supernovae type 1a we can explain most of the background from 1 keV to 10 GeV (from Zdziarski 1996, in preparation), as shown in Figure 6.

7. Conclusions

The X-γ spectra of radio-quiet Seyfert 1's have power-law components with $\alpha \sim 0.9$–1 at least in the range $\sim$ 2–200 keV. At higher energies, there is a cutoff, which if modeled as an exponential cutoff is constrained to 0.2 MeV $\lesssim E_c \lesssim$ 1 MeV. The cutoff energy is *not* $\sim$ 40 keV, as obtained by fitting the OSSE data alone in a narrow energy range and without including reflection (Johnson et al. 1994). The spectral component due to reflection from cold matter, possibly an accretion disk, hardens the X-ray spectra to $\alpha \sim 0.7$ and softens the γ-ray spectra to $\alpha \sim 1.2$.

The broad-band spectrum of Cyg X-1 is similar to the typical X-γ spectra of radio-quiet Seyfert 1's, however it is somewhat harder ($\alpha \sim 0.6 - -0.7$), and contains an additional, hard component, peaking around 200 keV.

The Seyfert 1 spectra can be modeled by optically thin, relativistic, thermal Comptonization. Optically thick nonrelativistic Comptonization is ruled out. Also, Comptonization by nonthermal electrons injected with small Lorentz factors is compatible with the present data. The thermal Comptonization is likely to take place in an electron corona above the accretion disk.

The spectra of NGC 4151, a Seyfert 1.5, are described by optically thick, mildly relativistic thermal Comptonization ($kT \sim 50$ keV, $\tau \sim 2$) in contradiction to the Seyfert 1's spectra. The data allow a small admixture of nonthermal processes only. The lack of Compton reflection component in the spectra suggests, that the hot source is not a disk corona.

The contributions from various classes of Seyferts fit well (with cosmological evolution) the XRB, with radio-quiet Seyfert 2's explaining the XRB peak at 30 keV.

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