X-RAYS AND GAMMA-RAYS FROM ACCRETION FLOWS ONTO BLACK HOLES IN SEYFERTS AND X-RAY BINARIES

Andrzej A. Zdziarski

N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

W. Neil Johnson

E. O. Hulburt Center for Space Research, Naval Research Lab, Washington, DC 20375, USA

Juri Poutanen

Uppsala Observatory, Box 515, S-75120 Uppsala, Sweden

Paweł Magdziarz and Marek Gierliński

Astronomical Observatory, Jagiellonian University, Orla 171, 30-244 Cracow, Poland

ABSTRACT

We review observations and theoretical models of X-ray/γ-ray spectra of radio-quiet Seyfert galaxies and of Galactic black-hole candidates (in the hard spectral state). The observed spectra share all their basic components: an underlying power law, a Compton-reflection component with an Fe Kα line, low-energy absorption by intervening cold matter, and a high-energy cutoff above ~ 200 keV. The X-ray energy spectral index, α, is typically in the range ~ 0.8–1 in Seyfert spectra from *Ginga*, *EXOSAT* and OSSE. The hard-state spectra of black-hole candidates Cyg X-1 and GX 339-4 from simultaneous *Ginga*/OSSE observations have $\alpha \simeq 0.6$–0.8. The Compton-reflection component corresponds to cold matter (e.g., inner or outer parts of an accretion disk) covering a solid angle of $\sim (0.4–1) \times 2\pi$ as seen from the X-ray source. The spectra are cut off in soft γ-rays above ~ 200 keV. The broad-band spectra of both Seyferts and black-hole sources are well fitted by Compton upscattering of soft photons in thermal plasmas. Our fits yield the thermal plasma temperature of ~ 100 keV and the Thomson optical depth of $\tau \sim 1$. A fraction of the luminosity emitted nonthermally appears to be small and it can be constrained to $\lesssim 15\%$ in the Seyfert galaxy NGC 4151. The spectra are cut off before 511 keV, which is strongly suggestive of a thermostatic role of $e^{\pm}$ pair production in constraining the temperature and optical depth of the sources. The source geometry is compatible with a patchy corona above a cold disk in Seyferts, but not in Cyg X-1. In the latter, the relative weakness of reflection is compatible with reflection of emission of a hot inner disk from outer disk regions.

Keywords: galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies – gamma-rays: observations – radiation mechanisms: thermal – stars: individual: (Cyg X-1, GX 339-4)

1. INTRODUCTION

Seyfert galaxies are the first class of objects in which we are able to directly probe the gravitational potential near a black hole. This has been achieved thanks to the discovery by the *ASCA* observatory (Tanaka, Inoue & Holt 1994) of broad Fe Kα lines from several Seyfert 1s (Tanaka et al. 1995; Fabian et al. 1995; Iwasawa et al. 1996). The width of the lines, $\sim c/3$ or more, requires the lines originate in large part at radial distances of $6GM/c^2$ or even less (Iwasawa et al. 1996). The peak energies of the narrow cores of the lines are close to 6.4 keV, which shows the lines are emitted by cold and dense media, with Fe being at most mildly ionized.

The lines originate when X-rays irradiate cold matter. Photons with energies above the Fe K edge, $\gtrsim 7$ keV, are able to ionize the K shell of an Fe atom or ion. Since the L shell is occupied (unless for He-like and H-like Fe ions), the ion becomes excited. The deexcitation proceeds in most cases through an L-to-K transition. The transition energy, ≥ 6.4 keV, goes into either an ejection of an outer shell (Auger) electron, or into emission of a Kα photon. The probability of the latter process is about 50% (e.g., George & Fabian 1991). The resulting fluorescent Kα line is broadened by the Doppler effect and gravitationally.

A very important process associated with the fluorescent formation of Fe Kα lines is Compton reflection (White, Lightman & Zdziarski 1988; Lightman & White 1988). In this process, X-rays and γ-rays (hereafter Xγ) irradiating the cold matter get Compton-scattered (in one or more scattering events) back to the observer. Compton reflection of a power-law spectrum typical for Seyferts forms a characteristic continuum peaked (in νF_ν) around 30 keV. Below the peak, bound-free absorption becomes important and incident photons are likely to get absorbed. The bound-free cross section of cosmic-composition matter increases (except at ionizatoin edge energies) with decreasing energy, and it becomes larger than the Thomson cross section below ~ 10 keV. Above the peak, Klein-Nishina effects become important. Namely, a photon loses a substantial part of its energy in a scattering, which occurs preferentially forward, and its cross section decreases with energy. These effect results in a steep cutoff of the reflected spectrum above ~ 100 keV. The presence of a Compton-reflected spectral component has been discovered in the spectra of Seyferts by *Ginga* (Pounds et al. 1990; Nandra & Pounds 1994). The relative normalization of the reflected component with respect to the direct one in the spectra of Seyfert 1s corresponds to the solid angle of the reflector close to 2π (Nandra & Pounds 1994; Zdziarski et al. 1995; Gondek et al. 1996). This strongly suggests that the reflector is a cold accretion disk. This conclusion is further supported by the fits to the Kα line profiles by emission of relativistic disks (extending to the minimum stable orbit, e.g., Tanaka et al. 1995) and the large equivalent widths of the Kα lines, EW~ 200 eV on average (Nandra et al. 1996).

Thus, the results of *ASCA* and *Ginga* lead to a picture with the Xγ emission in Seyfert 1s typically taking place above the surface of an accretion disk. As discussed above, we understand relatively well the reflected, secondary, component of the emission. On the other hand, the origin of the incident, *primary*, radiation is much less understood. In order to understand its origin, we need to study broad-band, Xγ spectra of Seyferts. In X-rays, the intrinsic spectra turn out to be simple power laws (see §2 below), which only weakly constrain their origin. A key observable needed to understand the origin of the primary spectra is the spectral shape at high energies, in particular any spectral break or cutoff, or a spectral feature. This key information can be provided by soft γ-ray observations by OSSE (Johnson et al. 1993) aboard *Compton Gamma Ray Observatory*, as well as future soft γ-ray experiments, e.g., *INTEGRAL* (Winkler 1994). In this work, we review the available Xγ spectra from Seyferts and discuss resulting constraints on physical processes in the radiation sources (see also reviews by Svensson 1996; Zdziarski et al. 1996).

We also discuss the spectral properties of Galactic black-hole candidates in the hard (so-called 'low') state (see Nowak 1995). We consider spectra of GX 339-4 and Cyg X-1. The spectra are very similar to those of Seyferts and consist of an underlying power-law, a Compton reflection component, and a high-energy cutoff at ~ 200 keV. This remarkable similarity between Seyfert and stellar-mass black-hole sources appears to reflect the shared origin of the emission from an accretion flow onto a black hole. We find that the intrinsic power laws with the cutoff in both classes of objects are well modeled by thermal Compton upscattering in mildly relativistic plasmas of moderate Thomson optical thickness ($kT \sim 100$ keV, $\tau \sim 1$).

2. SPECTRA OF IC 4329A AND OF AVERAGE SEYFERT SAMPLES

As yet, relatively few broad-band, Xγ spectra of Seyferts are available. Those include the spectrum of IC 4329A (a Seyfert 1) from *ROSAT*, *Ginga*, and OSSE (Madejski et al. 1995). The spectrum (fitted as in Zdziarski et al. 1996) is shown in Figure 1a. It consists of an underlying power law with the energy spectral index of $\alpha = 0.94 \pm 0.03$ and a reflection component corresponding to the solid angle of $\Omega/2\pi = 0.74^{+0.17}_{-0.16}$ (assuming the viewing anle of $30°$ in angle-dependent reflection Green's functions of Magdziarz & Zdziarski 1995 and using the elemental abundances of Anders & Grevesse 1989). There is a cutoff in the spectrum above ~ 200 keV; when the spectrum is fitted with an e-folded power law, the e-folding energy is $E_{\rm c} = 0.3^{+0.2}_{-0.1}$ MeV. (We use XSPEC, see Arnaud 1996, for spectral fitting, and the quoted errors are for 90% confidence limit based on a $\Delta\chi^2 = 2.7$ criterion.)

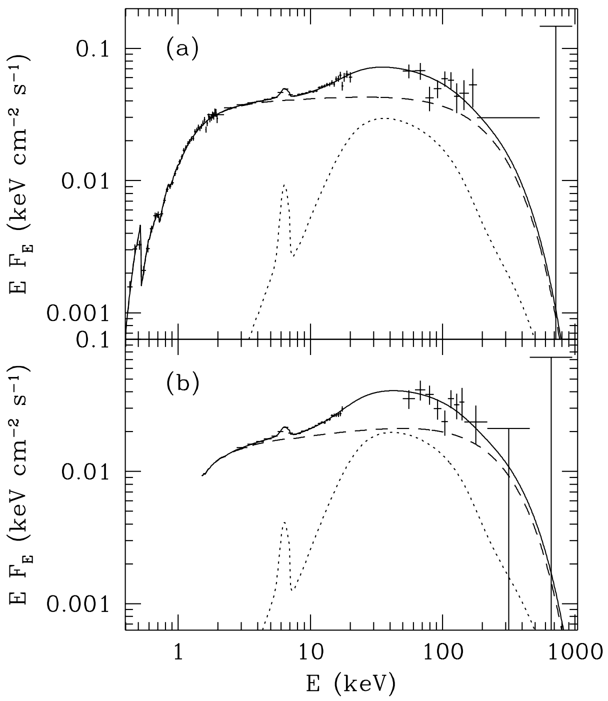

Figure 1: The broad-band Xγ spectra of Seyfert 1s. *(a)* The *ROSAT*/*Ginga*/OSSE spectrum of IC 4329A. *(b)* The average spectrum (*crosses*) of 5 radio-quiet Seyfert 1s detected by both OSSE and *Ginga*. The upper limits here and in figures below are 2-σ. The dashed curves represent the best-fit thermal Comptonization spectra of PS96. The dotted curves represent the absorbed reflected component including the fluorescent Fe Kα line. The solid curves give the sum.

A similar cutoff above ~ 200 keV is seen in the average spectrum of 5 radio-quiet Seyfert 1s observed 25 times by *Ginga* and 14 times by OSSE (Gondek et al. 1996), shown in Figure 1b. The parameters of the fit with an e-folded power law are $\alpha = 0.90 \pm 0.05$, $\Omega/2\pi = 0.76 \pm 0.15$, and $E_{\rm c} = 0.7^{+2.0}_{-0.3}$ MeV (assuming the abundances of Anders & Ebihara 1982). A very similar average spectrum is also obtained for 7 radio-quiet Seyfert 1s observed 41 times by *EXOSAT* and 18 times by OSSE (Gondek et al. 1996).

A major question for our understanding of the AGN phenomenon is the origin of the underlying cut-off power law spectrum. Models with synchrotron emission predict simultaneous IR/X-ray variability, which is not observed. Also, the cutoff above 200 keV would then require a fine-tuned sharp cutoff in the distribution of the emitting relativistic electrons. The most likely physical process responsible for the underlying spectra appears to be Compton scattering in a thermal plasma. The formation of power-law spectra in this model is due to superposition of relatively narrow scattering profiles from subsequent orders of scattering (e.g., Svensson 1996). The spectral index is a function of the optical depth and temperature of the plasma, and there is high-energy cutoff in the spectrum at energies above a few times kT. The plasma in Seyfert 1s is *not* optically thick (Zdziarski et al. 1994), which precludes the use of formulae of Sunyaev & Titarchuk (1980). Until recently, there have been no ready-to-use, accurate, formulae for spectra of $\tau \lesssim 1$ plasmas (as discussed in Poutanen & Svensson 1996, hereafter PS96). Instead, power-laws with exponential cutoffs have been commonly used (see above).

Here, we use the code of PS96 for thermal Comptonization in active regions above the surface of a disk. The active regions are assumed to have the form of hemispheres (with the radial optical depth equal τ) on the disk surface. The code gives highly accurate results, which agree with those obtained with a Monte Carlo method (Stern et al. 1995; PS96). Here, we use this code to fit IC 4329A (see also Poutanen, Svensson & Stern 1997) and the average *Ginga*/OSSE spectrum of Seyfert 1s (Gondek et al. 1996). Our preliminary fits give $\tau = 1.3^{+0.4}_{-0.2}$, $kT = 100^{+10}_{-30}$ keV, and $\tau = 1.0^{+0.4}_{-0.2}$ and $kT = 130^{+30}_{-40}$ keV, respectively. The model spectra are shown by the curves in Figures 1a, b.

The statistics of the OSSE data of the two above spectra is relatively limited, and thus the cutoff is not very well constrained. Therefore, we also consider the co-added spectrum of all Seyfert 1s (except NGC 4151) detected by OSSE through 1995 (McNaron-Brown et al. 1997). The sample consists of 29 observations of 12 Seyfert 1s. NGC 4151, whose flux in the OSSE range is an order of magnitude higher than that of other Seyfert 1s, is excluded in order to avoid the dominance of the spectrum by a single object. That spectrum, shown in Figure 2a, has the shape indistinguishable from that of the co-added OSSE spectra of Gondek et al. (1996). By this we hereafter mean that the two spectra can be fitted with the same model with $\Delta\chi^2 < 2.7$ with respect to the sum of χ^2 for the two individual fits. The present OSSE spectrum shows a clear high-energy cutoff above $\sim$ 150 keV. However, the OSSE spectrum starts at 50 keV only and it does not allow to determine the X- ray spectral index and the normalization of the reflection component, which quantities are both are important for determining the plasma temperature. Therefore, while fitting the average OSSE spectrum we constrain the X-ray spectrum at the best-fit values obtained for the *Ginga*/OSSE average spectrum ($\alpha = 0.90 \pm 0.05$, $\Omega/2\pi = 0.76 \pm 0.15$). Our preliminary fit results are again very similar to those above, $\tau = 1.2^{+0.4}_{-0.3}$ and $kT = 110^{+40}_{-30}$ (shown by the curves in Figure 2a).

We compare now the average OSSE spectrum of Seyfert 1s with that of Seyfert 2s detected by OSSE (8 objects observed 19 times through 1995; McNaron-Brown et al. 1997). We find that the spectrum, shown in Figure 2b, is statistically indistinguishable from that of Seyfert 1s above, and it again shows a cutoff above $\sim$ 200 keV. When we fit it with the best-fit constraints at X-rays as obtained by Gondek et al. (1996) for Seyfert 1s (except that the disk viewing angle, important for reflection, is fixed at 60°, compatible with the AGN unified model, Antonucci 1993), we obtain $\tau = 1.1^{+0.2}_{-0.2}$ and $kT = 110^{+20}_{-20}$ (corresponding to the curves in Figure 2b). The fact that these fits give results virtually identical to those of Seyfert 1s strongly supports the unified AGN model, according to which Seyfert 1s and 2s differ only by orientation with respect to the observer (Antonucci & Miller 1985; Antonucci 1993). It also shows that the characteristic column densities of the obscuring torii in the considered

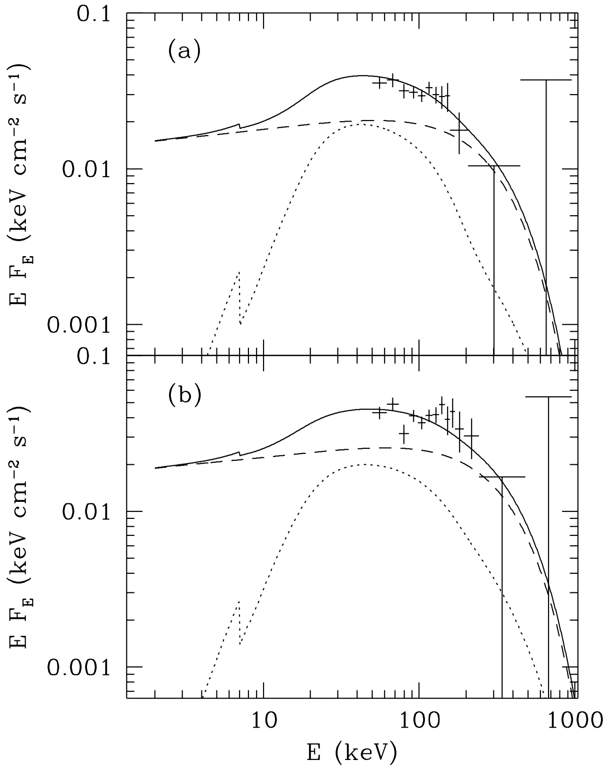

Figure 2: The average spectra (*crosses*) of radio-quiet Seyferts detected by OSSE (McNaron-Brown et al. 1997). The dashed curves represent the best-fit thermal Comptonization spectra of PS96 (without showing absorption at soft X-rays). The dotted curves represent the reflected component. The solid curves give the sum. *(a)* The Seyfert 1 sample (excluding NGC 4151). *(b)* The Seyfert 2 sample.