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X/γ-rays from Active Galactic Nuclei

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Abstract. Recent progress using RXTE and *BeppoSAX* to study the X/γ emission from radio-quiet active galactic nuclei, i.e., Seyfert galaxies, is reviewed. These satellites allow simultaneous broad-band spectra extending from 0.1–200 keV to be observed for the first time and allow the various spectral components to be determined with some certainty. In particular, the new observations support the unified model of Seyfert galaxies. Most importantly, it has been found that a large fraction of Seyfert 2 galaxies have Compton-thick tori surrounding their nuclei. Spectral transitions in Seyfert galaxies are discussed, as well as recent efforts trying to synthesize the cosmic X/γ-ray background. Finally, thermal Comptonization in these sources are discussed.

1. Introduction

The launches of the *Rossi X-ray Timing Explorer* (RXTE; Dec 1995; 2–200 keV) and *BeppoSAX* (April 1996; 0.2–200 keV) have, for the first time, allowed the simultaneous determination of the broad-band X/γ-spectra of active galactic nuclei (AGN). Previous studies depended on combining simultaneous or nonsimultaneous "narrow-band" spectra from various satellites, often giving spectral gaps, in particular, in the 10–50 keV region. Since AGN vary in the X-rays on time-scales down to days or even hours, simultaneous measurements are necessary, but such only existed for a handful objects before RXTE and *BeppoSAX*. The new broad-band studies confirm many of the earlier results and indications but have also generated several new results.

In this review, the focus is on the new observations and on what consequences these observations have for our understanding of the physical processes generating the X/γ-spectra of AGN. Some recent relevant reviews are Svensson (1997, 1999), Poutanen (1998, 1999), Brandt (1999), Coppi (1999), Madejski (1999), Matt (1999), Reynolds (1999), and Zdziarski (1999). The similarities between AGN and galactic black-hole binaries means that much relevant material can also be found in Zdziarski (2000, these Proceedings).

2. Classes of AGN

After the launch on April 1991 of the *Compton Gamma Ray Observatory* (CGRO), which covers the gamma-ray spectral range, we got, for the first time, a full broad-band view of AGN spectra and thus reliable estimates of their total luminosities and the spectral ranges where most of the luminosity was emitted. As described in Dermer & Gehrels (1995), AGN fall into two distinct classes: the γ-loud and the γ-weak AGN. The γ-loud AGN are the luminous blazars where we are looking down into a relativistic jet emerging from the AGN. Here, the power emerges in two broad-band humps, one due to nonthermal synchrotron emission peaking in the IR-optical spectral range, the second due to Compton-scattering peaking in the MeV–GeV spectral range. The γ-weak AGN, on the other hand, are the less luminous Seyfert and radio galaxies (being spiral and ellipticals, respectively), where the spectra extend from radio frequencies to the soft γ-rays (100s of keV). These spectra have approximately equal power per logarithmic frequency interval but show many features, in particular, three broad-band spectral peaks at infrared, UV, and hard X-ray frequencies. The fast time variability of the UV to soft γ-ray spectra indicates that this emission is "nuclear" radiation originating in the accretion flow very close to the black hole. The slowly varying, broad-band infrared spectral peak originates at larger distances, most likely being due to nuclear radiation being reprocessed by dust. The nuclear spectra has been studied for more than 20 years, yet not much is known about the physical conditions close to the supermassive black holes in AGN.

Both Seyfert (normally being radio-weak) and radio galaxies comes in two types based on optical classification. Seyfert 1 and the broad-line radio galaxies show Doppler-broadened broad (up to 10 000 km/s) and narrow (up to perhaps 1000 km/s) emission lines, while the Seyfert 2 galaxies and the narrow-line radio galaxies show only the narrow emission lines. The broad lines originate in fast-moving photo-ionized 10^4 K gas clouds within 1 parsec of the central source, while the narrow lines originate in slower moving clouds at kiloparsec distances.

In the unified scheme for Seyfert galaxies (e.g., Antonucci 1993), we are directly viewing the central X-ray source and broad-line region in Seyfert 1 galaxies, but our line-of-sight passes through an optically opaque, molecular torus in Seyfert 2 galaxies, obscuring both the central source and the broad-line region but not the narrow-line region. The photo-ionized narrow-line gas lies in an ionization cone whose half-opening angle is determined by the geometry of the obscuring torus. In some Seyfert 2 galaxies, we still see weak polarized broad lines being reflected by electrons in the ionization cone. In standard accretion disk scenarios for the central X-ray source, the unified models imply that our viewing angle (i.e., the angle between the disk normal and the line-of-sight) is less than the half-opening angle of the ionization cone for the case of Seyfert 1s. Half-opening angles inferred from optical observations are typically 30–40 degrees, which means that in Seyfert 1s we are viewing the accretion disk from directions that are closer to face-on than to edge-on.

3. Seyfert 1 Galaxies

Prior to the launches of RXTE and *BeppoSAX*, broad-band studies were only possible for the very few brightest Seyfert 1s, such as IC 4329A and NGC 4151, or for the average X/γ-spectra of several (weaker) Seyfert 1s (see reviews by, e.g., Svensson 1997; Zdziarski 1999, and references therein). The picture that emerged is the following. The spectrum consists of two main components: 1) an intrinsic power law with photon index $\Gamma \approx 1.9$ with a rather unconstrained turnover energy of about one to a few hundred keV, and 2) a reflection component caused by cold (neutral) reflecting matter subtending a solid angle, $\Omega \sim 1\text{–}2\pi$ as viewed from the X-ray source. The reflection component consists of a fluorescent Fe line at 6.4 keV and a broad peak at about 30 keV shaped by Compton downscattering at energies larger than the peak energy, and by photoelectric absorption at lower energies. In addition, a small column depth of neutral material along the line-of-sight (most likely in the host galaxy) causes absorption at smaller energies. In addition, there may also exist a "warm" ionized absorber giving rise to absorption edges.

Two of the core programs of *BeppoSAX* concern the broad-band spectra and spectral variability, respectively, of Seyfert 1 galaxies. More than a dozen of these objects have been observed, so far (see, e.g., Matt 1999 for a review), confirming most of the previous results.

The *BeppoSAX* observations so far have given relatively firm constraints of the cutoff energy of the intrinsic spectrum for at least 5 of the brightest objects (NGC 4151: Piro et al. 1998; IC 4329A: Perola et al. 1999; MCG-6-30-15: Guainazzi et al. 1999b; NGC 5548, Mrk 509: Matt 1999). The X-ray brightest (2–10 keV) Seyfert 1, NGC 4151, has the most well-constrained e-folding cutoff energy, 70 ± 15 keV, which is unusually small compared to the other measured cutoff energies. The second brightest Seyfert 1, IC 4329A, for example, has its cutoff at 270^{+167}_{-80} keV, and for most of the remaining objects, there is only a lower limit to the cutoff energy of one to a few hundreds of keV (see Matt 1999 for a table). One concludes that there is no unique cutoff energy but rather a range of values covering about a decade in energy ($\sim$ 50–500 keV) with an, as yet, unknown distribution.

4. Seyfert 2 Galaxies

In the unified scenario, the Seyfert 2 phenomenon is generated by a Seyfert 1 nucleus obscured by a molecular torus. The intrinsic, exponential cutoff power-law component and any reflection component originating close to the X-ray source will, while passing through the molecular torus, experience photoelectric absorption to a degree that depends on the column depth. For column depths larger than $1.5 \times 10^{24}\,\mathrm{cm}^{-2}$, the torus is Compton-thick, all nuclear X-rays below 10–20 keV are photoelectrically absorbed, and radiation at larger energies is strongly reduced by Compton diffusion (see, e.g., Matt, Pompilio, & La Franca 1999). This reduction of the nuclear radiation allows other spectral components to become visible. These are cold reflections of the nuclear spectral components from the inner surface of the torus opposite to the viewer and Compton scattering of the nuclear spectral components on the "warm" ionized gas that is likely to exist in the ionization cone of the torus (i.e., the "warm" absorber in Seyfert 1s). Depending on the viewing angle, the cold reflection component may be partially covered by the torus, and one must account for the transmission through the torus. There are thus several possible spectral components, and the determination of these requires good broad-band spectral coverage. Verification of the above picture would provide support for the unified model.

As for Seyfert 1s, broad-band studies of Seyfert 2s prior to the launches of RXTE and *BeppoSAX* were limited to a few bright objects (e.g., NGC 7172:

Ryde et al. 1997) or the average spectra of several weaker ones. The obscuring column depths from the *Ginga* observations (2–18 keV) were found to lie in the range $N_{\rm H} \sim 10^{22}$–3×10^{23} cm^{-2} (Smith & Done 1996). A few extreme cases were: NGC 4945, found to be Compton-thick and which showed a strongly absorbed transmitted component becoming dominant above 10 keV (Done, Madejski, & Smith 1996); the Circinus galaxy, probably dominated by a strong reflection component (Matt et al. 1996); and NGC 1068, probably very Compton-thick and dominated by the scattered component in the *Ginga* energy range.

It was clear that X-ray surveys were biased against Compton-thick sources, being weak at 2–10 keV where a possible scattered component would dominate at a level of only a few percent of the direct nuclear component (depending on the Thomson depth of the "warm" scatterer). But for Compton-thick sources, much brighter reflected or transmitted components might be lurking at energies above 10 keV. Considerations of a flux-limited sample based on an isotropic luminosity indicator, the [O III]-flux, has led to a new picture (Risaliti, Maiolino, & Salvati 1999; Bassani et al. 1999) where most Seyfert 2s are heavily obscured and 50% are Compton-thick. The number of sources per $\log N_{\rm H}$-interval increases approximately linearly with $\log N_{\rm H}$ from $N_{\rm H} \sim 2 \times 10^{22}$–$5\times10^{23}$ cm^{-2} (an analytical approximation used by, e.g., Pompilio, La Franca, & Matt 2000).

Seyfert 2 galaxies are studied in three core programs for *BeppoSAX*: bright Compton-thin sources, bright Compton-thick sources, and fainter sources in the [O III]-flux limited sample discussed above. Many sources have already been observed and initial results have already been published (for a more comprehensive review, see Matt 1999).

Of most interest is, perhaps, the Compton-thick sources. The previous pictures of Circinus and NGC 1068 are confirmed (Matt et al. 1999; Guainazzi et al. 1999a). Besides the scattered and reflected component in Circinus, a transmitted component starts to dominate above about 15 keV. The e-folding cutoff is well-constrained to be about 50–80 keV depending on details, which makes the primary spectrum resemble that discussed for NGC 4151 above. NGC 1068 does not seem to have a transmitted component (Matt et al. 1997). Other sources have also been found to be Compton-thick: Mrk 3 (Cappi et al. 1999), NGC 7674 (Malaguti et al. 1998), and NGC 6300 (RXTE, Leighly et al. 1999). In Mrk 3 (being marginally Compton-thick), a transmitted component dominates above 10 keV. Any high-energy cutoff was constrained to be above 150 keV (in contrast to Circinus). Most of the X-ray weak sample of 8 sources studied by Maiolino et al. (1998) was found to be Compton-thick.

5. The R-Γ Correlation

Zdziarski, Lubiński, & Smith (1999, also reviews by Zdziarski 1999; 2000) found a strong correlation between the reflection parameter, $R \equiv \Omega/2\pi$, and the photon index, Γ, of the intrinsic X-ray power law for both Seyferts and galactic black-hole binaries. This study used archival *Ginga* data for 47 observations of 23 Seyfert galaxies (both type 1 and Compton-thin type 2). The correlation was found to be valid both for the sample of Seyferts (with R extending from 0 to 2, and Γ from 1.5 to 2.2) as well as for different observations of the same source (e.g., NGC 5548, but then the ranges of R and Γ seem to be narrower,

~ 0.2). RXTE observations of NGC 5548, on the other hand, show much less correlation (Chiang et al. 2000), while the RXTE observations of MCG–6-30-15 show a strong correlation for four different flux states (i.e., both R and Γ correlate with the 3–20 keV flux, see Table 2 in Lee et al. 1999). Additional RXTE data are displayed in Zdziarski (2000, these Proceedings). The R-Γ correlation is important as it has implications for the geometry of the X-ray source. The simplest geometry is that of a spherical, hot plasma cloud generating the intrinsic X-ray power law, with a cold disk surrounding the cloud as well as extending into the cloud to an inner disk radius. A decreasing inner disk radius increases the Compton reflection (i.e., larger R), as well as provides more soft photons to be Comptonized in the hot cloud (resulting in softer spectra, i.e., larger Γ; see Zdziarski et al. 1999; Zdziarski 2000, these Proceedings for further details). An alternative explanation for the R-Γ correlation is given in Beloborodov (1999a, 1999b), where anisotropic Compton scattering of the soft disk-photons in a mildly relativistic outflow (Beloborodov 1999c) of hot gas causes less photons to be backscattered into the disk and thus less reflection. Scattering in the outflow may also explain the unusual polarization behavior near the Lyman edge observed in some quasars (Beloborodov & Poutanen 1999).

It must be remembered that the environments in Seyferts (at least in Seyfert 2s) are "dirty" as compared to black-hole binaries due to possible ongoing star formation, the existence of the reflecting molecular torus, and the "warm" reflecting gas, all of which will introduce scatter in any R-Γ correlation.

6. Spectral State Transitions in Seyferts?

Are there spectral states among Seyferts corresponding to the spectral states of galactic black-hole binaries, in particular, the hard and the soft state of those sources (see Zdziarski 2000, these Proceedings)? As Zdziarski points out, the *Ginga*/OSSE spectrum of the Seyfert 1 galaxy NGC 4151 is virtually identical to the corresponding spectrum of the black-hole binary GX 339-4. And do Seyfert galaxies ever enter the very high state or the quiescent state of X-ray transients? There is some intriguing evidence that they might do that, the major problem being that the time scales between transitions are so long (scaling with the black-hole mass to some power) that we may never catch them in the act unless the source is sufficiently small (and thus weak).

One such candidate source is the low luminosity and highly variable Seyfert 1 galaxy NGC 4051. It was observed May 9–11, 1998 by *BeppoSAX*, RXTE, and EUVE, and it was found that the standard Seyfert 1 spectrum seen by ASCA in 1994 was gone, leaving a Compton-thick, Seyfert-2–like spectrum consisting of a cold reflection bump together with a prominent iron line (Guainazzi et al. 1998b; Uttley et al. 1999). The 2–10 keV luminosity had dropped by a factor of 20. The interpretation is that the Seyfert 1 nucleus had turned off, leaving only the residual Compton reflection on the surrounding torus echoing the past activity of the nucleus. RXTE monitoring showed that the nucleus had shut off about 150 days prior to the observations, implying the reflecting surface to be more than 10^{17} cm away from the nucleus. New observations 1.5 months later showed the source to be back in its normal Seyfert 1 state again. The ultradim state of NGC 4051 might correspond to the quiescent state of X-ray transients, with the difference that, in Seyferts, the surrounding torus continues to reflect nuclear radiation for at least a few months. Monitoring the eventual decline of this reflected radiation will give constraints on the geometry and size of the reflecting material.

The archival and published data of the Seyfert 2 galaxy NGC 2992 over 16 years showed that the 2–10 keV luminosity had decreased by a factor of 20 and that the reflection component had become a factor 5 stronger relative to the intrinsic power-law continuum (Weaver et al. 1996). The estimated lag between the nuclear power-law continuum and the reflection component is 10 years, placing the reflecting torus at a distance of a few parsecs with probably no reflection taking place in the nuclear source itself. In this obviously larger source, we are actually following a slow-state transition from a bright to a dim state taking place over decades.

There are other freak objects, e.g., 1H0419-577, which shows a Seyfert 1 spectrum in the optical range but with unusual X-ray properties, including a transition from a soft to hard state in the ROSAT band (Guainazzi et al. 1998a).

There have been suggestions (Pounds, Done, & Osborne 1995) that the Narrow Line Seyfert 1 (NLS1) galaxies, with their strong, steep, and variable soft X-ray continua (for a review on NLS1, see Brandt 1999), are the Seyfert state corresponding to the soft, high state of black-hole binaries. Also, at harder X-ray energies (> 2 keV), these sources are, on average, softer than normal Seyfert 1s, although the difference is not that large ($\Gamma \sim 2.1$ as compared to $\Gamma \sim 1.9$, Vaughan et al. 1999). There are several differences at all wavelengths from the radio to X-rays (see summary in Taniguchi, Murayama, & Nagao 1999), and it is difficult for most scenarios to explain all of these. Taniguchi et al. (1999) prefer a viewing-angle scenario where the NLS1 are those cases where Seyferts are viewed directly pole-on.

The matter of whether there are clear correspondences between the states seen in black-hole binaries and the few indications of such states in Seyfert galaxies is far from settled.

7. The X/γ-ray Background

Seyfert 1 and Seyfert 2 galaxies are thought to make up most of the cosmic X-ray background above 1 keV. Recent efforts to model the 1–100 keV X-ray background (e.g., Gilli, Risaliti, & Salvati 1999; Pompilio et al. 2000) include, e.g., the observed Seyfert 2 distribution of $N_{\rm H}$ between 10^{21} and $10^{25}\,{\rm cm}^{-2}$, the soft X-ray luminosity function of Seyferts and its evolution, and the cosmological density evolution of Seyferts. Pompilio et al. (2000) also account for the transmission of X-ray radiation through a Compton-thick medium in Seyfert 2s. Both of the quoted papers find that the fraction of Seyfert 2s should have been larger in the past, and they must thus have undergone stronger evolution than Seyfert 1s. The ROSAT integral source counts (0.3–3.5 keV) are well reproduced, but the *BeppoSAX*/HELLAS integral counts in the 5–10 keV band can only be reproduced if the HEAO-1 data are normalized upwards by about 30% to be consistent with the normalization obtained with *BeppoSAX*/MECS. Best fits in Pompilio et al. (2000) then require the ratio of Seyfert 2s to Seyfert 1s to increase from a local value of about 5 to about 8 at a redshift of unity before a sharp decline sets in. This decreasing fraction of Seyfert 2s might just be an apparent one caused by more Seyfert 2s being Compton-thick (and thus invisible in X-rays) at larger redshifts. The models include many assumptions and prescriptions (e.g., the evolutionary scenarios) and are not unique. Missions such as XMM and *Chandra* are able to discriminate between different scenarios.

It has been suggested (Stecker, Salamon, & Done 1999) that Seyferts also possess a nonthermal MeV-tail, just as for galactic black-hole binaries in their hard state. This (presently unobservable) spectral tail could then account for some or most of the cosmic background in the 1–10 MeV range.

8. Thermal Comptonization in Seyfert Nuclei

Since the nondetections of γ-rays by CGRO/COMPTEL and the high-energy cutoffs indicated by CGRO/OSSE, attention has been focused on thermal Comptonization models where the spectral cutoff occurs at photon energies of the order of the electron temperature. In such models, mildly relativistic thermal electrons Compton-scatter soft UV-photons into the X-ray range. Part of this radiation is intercepted and reprocessed by cold matter (e.g., a cold accretion disk or a more distant molecular torus) into mainly soft photons, a fraction of which may enter the hot active region and be Comptonized.

Two different methods have been used to solve the full radiative transfer/ Comptonization problem in mildly relativistic thermal plasmas, accounting for energy and pair balance as well as reprocessing by a cold disk (including angular anisotropy and Klein-Nishina effects).

The first method is based on the Nonlinear Monte Carlo (NLMC) method developed by Stern (1985) and described in Stern et al. (1995a). Similar codes now exist in a few research groups around the world. Calculations so far (Stern et al. 1995b, also see Svensson 1997) have been limited to coronal slabs (1D) or active regions (2D) in the shape of hemispheres or spheres at different elevations above the cold disc.

The second method is based on the iterative scattering method (ISM), where the radiative transfer is exactly solved for each scattering order separately (Poutanen & Svensson 1996). The ISM code is a 1D code, but it can also treat quasi-2D radiative transfer in cylinders/pill boxes and hemispheres, as well as some other geometries (Poutanen 1999). The full Compton-scattering matrix is used, allowing solution of polarized radiative transfer in thermal, relativistic plasmas (useful for modelling future X-ray polarimetric observations). The advantage of the ISM code is that it is much faster than corresponding NLMC codes and can easily be implemented in XSPEC.

From a pedagogical viewpoint, the problem can be divided into two parts: 1) solving the energy balance for a given geometry, and 2) solving the pair balance. If there are no or few pairs, the latter can be neglected.

For coronae of a given geometry and in energy balance, there exists a unique relation between T_e and τ_T, where T_e is the volume-averaged, coronal temperature and τ_T is a characteristic Thomson-scattering optical depth of the coronal region (see Figure 3 in Svensson 1997, and Figure 2 in Poutanen 1999). Geometries that have been considered are a slab corona sandwiching a cold disk, active coronal regions atop the disk in the shape of hemispheres or spheres at different elevations, and a central hot cloud surrounded by a disk partly extending into the cloud (see discussion in Poutanen 1999). For each relation (i.e., for each geometry), the Compton amplification, the generalized Kompaneets parameter, $y \equiv \tau_T(1+\tau_T)(4\Theta+16\Theta^2)$, and the slope of the Comptonized spectrum are approximately constant. Here, $\Theta \equiv kT_e/m_ec^2$. The parameter $y \sim 0.49$ for slabs, ~ 2.0 for hemispheres, and ~ 2.3 for spheres (of radius R) on the surface, and 5.9 for spheres elevated to the height R. The less the feedback of reprocessed soft photons from the cold material is, the more the active region is photon starved, the larger is y, and the flatter is the Comptonized spectrum.

Solving the pair balance for the combinations of (T_e, τ_T) obtained above gives a unique dissipation compactness, ℓ. Here, $\ell \equiv (L/R)(\sigma_T/m_ec^3)$ characterizes the dissipation, with L being the power providing uniform heating in the hot active region of size or thickness R. Figure 3b in Svensson (1996) shows T_e as a function of ℓ for different geometries. For hemispheres and spheres at different elevations and for the interesting temperature range 100–500 keV, the empirical relationship is simply $kT_e \sim 1000\,\mathrm{keV}/\ell^{1/3}$. For a given compactness, this is the maximum possible temperature with the pairs acting as a thermostat locking the temperature to this value (e.g., Svensson 1984). Pair-free plasmas must have lower temperatures.

Most fittings of observed spectra use prescriptions which give parameters such as spectral indices, cutoff energies, et cetera. Few fittings has been made, using the Comptonization models discussed above, that would provide temperatures, Thomson depths, and compactnesses. Using the ISM code for a hemisphere atop a disk, physical fits were made to the older data of a few individual sources and to co-added spectra from Seyfert 1s and Seyfert 2s, as well as broad-line radio galaxies (Zdziarski 1999, and references therein). In all cases, $kT_e \sim 100\,\mathrm{keV}$ and $\tau_T \sim 1$. If, on the other hand, a slab-type corona is used, τ_T is about a factor 3 smaller. Physical fits to *BeppoSAX* and RXTE data seem not to have been made, so far. However, the temperature can approximately be determined from the fitted e-folding cutoff energy, E_c, as $kT_e \sim E_c/1.6$, implying temperatures in the range 100 to at least a few 100 keV.

Why do the temperatures have values in this narrow range? There are two likely possibilities. First, if the compactnesses of the radiating coronal regions have reasonable values of the order 10–1000 (e.g., Svensson 1994), and if there are few background electrons in the energy dissipation region, the plasma will become pair-dominated, and the temperature will hit the pair-thermostat limit, $kT_e \sim 1000\,\mathrm{keV}/\ell^{1/3} \sim 100 - -300\,\mathrm{keV}$, which is the observed range. Two sources do not fit this scheme: the Seyfert 1 NGC 4151 and the Compton-thick, Seyfert 2 Circinus galaxy that has cutoff energies of the order of 50–70 keV—too small to allow intensive pair production. It is most likely that these two sources are not pair dominated, but there are also other explanations (see Poutanen et al. 1996). Second, the electron cooling rate in a plasma increases rapidly above 10^9 K (i.e., above 100 keV) due to rapidly increasing Compton (and possibly synchrotron) cooling. In most hot accretion models, this locks the electron temperature around 100 keV in the innermost parts of the accretion flow.

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