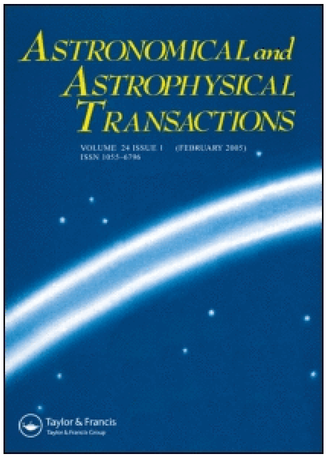

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X-RAYS FROM RADIO-QUIET AGN: OBSERVATIONS AND MODELS

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The X-ray emission properties of radio-quiet AGN are reviewed, with particular emphasis on observations and models concerning the interaction of X-ray photons with the matter around the black hole.

KEY WORDS Radio-quiet AGNs, X-ray emission

1 INTRODUCTION

These are very important years for X-ray astronomy, as the launches of *Chandra* and *XMM-Newton* have provided a dramatic improvement in angular and energy resolutions and in sensitivity. The most important results already achieved by these two satellites will be mentioned below, but most of this review is necessarily based on the results obtained by satellites of the previous generation (*ROSAT*, *ASCA*, *BeppoSAX*). Well established results will be outlined, as well as open questions which will be addressed and hopefully solved by the new missions.

In Figure 1 a typical X-ray spectrum is shown, with the various spectral components shown separately. In Figure 2 a real spectrum, i.e. that obtained by *BeppoSAX* on the Seyfert 1 galaxy IC 4329A, is shown.

2 PRIMARY CONTINUUM

For many years it has been customary to fit the primary continuum with a simple power law, as the quality of the data was not good enough to measure deviations for such a simple model. *CGRO/OSSE* (Gondek *et al.*, 1996) and *BeppoSAX* (e.g. Matt, 2000 and references therein) showed that at high energies, say above 100 keV or so, a cut-off is usually present. Assuming, as widely accepted, that the emission is due to Inverse Compton scattering by hot electrons of UV/soft X-ray

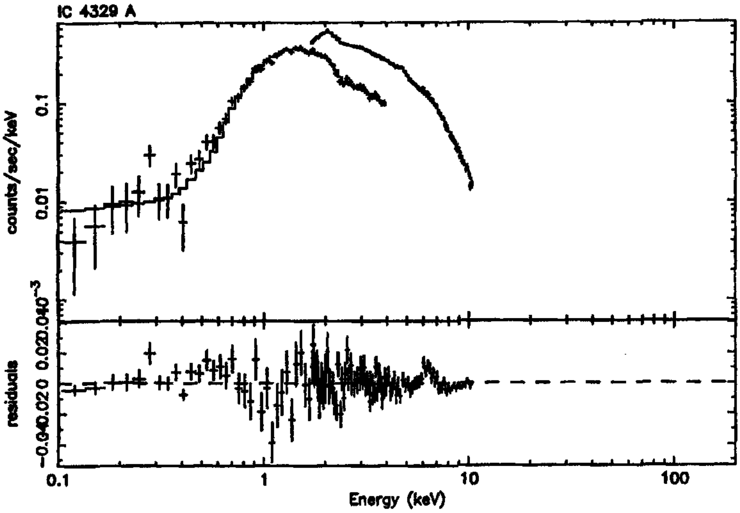

Figure 1 The typical X-ray spectrum of a Seyfert 1 galaxy, composed of: a primary emission with energy photon index ~ 1 and a high energy cut-off; a Compton reflection continuum, in the form of a broad hump peaking around 20–30 keV; a relativistically broadened iron Kα fluorescent line; and absorption by ionized matter. Absorption edges due to the warm absorber are also shown. The solid line is the total spectrum.

photons, the presence of such a cut-off may suggest that the electrons have a thermal distribution or, at least, that a characteristic energy in the electron distribution does exist (Ghisellini and Haardt, 1994).

Further spectral subtleties are expected in realistic Comptonization models (see e.g. Haardt and Maraschi, 1993; Poutanen and Svensson, 1996). We are possibly just starting to observe them (e.g. Petrucci *et al.*, 2000; Zdziarski *et al.*, 2000), but clearly we need better instruments to derive the main parameters of the emission mechanism. The hope is that *XMM* data will be good enough to do this, at least on the dozen or so brightest sources.

3 THE WARM ABSORBER

In at least half of the Seyfert 1s observed by *ASCA* (Reynolds, 1997; George *et al.*, 1997) there is evidence of absorption by ionized matter (the so-called 'warm absorber'), whose main features are the oxygen absorption edges.

Chandra, thanks to its transmission gratings, is starting to provide a much deeper knowledge of the ionized matter (*XMM-Newton* is expected to do the same). For instance, in the case of NGC 5548 the motion of the ionized matter has been measured, showing that it is outflowing with a velocity of a few hundred km s^{-1} (Kaastra *et al.*, 2000). Emission lines are also evident; they are redshifted with respect to the absorption lines, as expected if the outflowing matter has a spherical

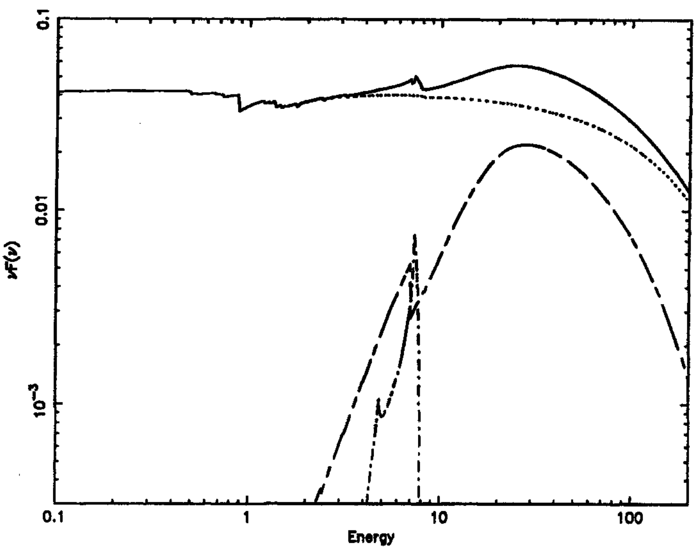

Figure 2 The X-ray spectrum of a bright Seyfert 1 galaxy, IC 4329A, obtained by *BeppoSAX*. Data has been fitted with a simple power law absorbed by our own Galaxy, in order to illustrate, in the residual, the other components.

distribution. In particular, the He-like triplet has been resolved, permitting one to put constraints on the density of the matter.

4 REFLECTION COMPONENTS

A fraction of the primary X-ray emission illuminates the circumnuclear matter, is absorbed and partly reflected. Both the accretion disc around the black hole, and more distant matter (i.e. either the Broad Line Region or the molecular torus) may be involved in this process.

The reflection spectrum consists of a continuum (usually referred to as the Compton reflection component) plus fluorescent lines, by far the most important among them (and the only one discussed here) being the iron Kα line.

4.1 Compton Reflection Continuum

The shape of the Compton Reflection continuum derives from the balance between photoelectric absorption and Compton scattering (Lightman and White, 1988; Guilbert and Rees, 1998). The photoabsorption cross section decreases with energy approximately as $E^{-3.5}$, while the Compton cross section stays constant, until the Klein–Nishina decline. At low energies, the former dominates and most photons are therefore absorbed. As energy increases, the fraction of scattered photons also increases, and above ~10 keV (where the two cross sections are equal) scattering dominates. Above a few tens of keV, Compton downscattering becomes important, and the reflected spectrum decreases again. The overall shape is therefore a broad hump peaking around 30 keV (see George and Fabian, 1991; Matt *et al.*, 1991 for further details).

The reflection component was discovered by *GINGA* (Pounds *et al.*, 1990; Nandra and Pounds, 1994); *BeppoSAX* has confirmed that it is almost ubiquitous in Seyfert Galaxies (e.g Matt, 2000 and references therein).

The shape of the Compton Reflection continuum is in principle sensitive to GR distortions occurring in the innermost part of the accretion disc (see e.g. Martocchia *et al.*, 2000 and references therein). However, these distortions are, especially in AGN, not easily measurable with the present generation of X-ray detectors; a much better way to distinguish between reflection occurring in the accretion disk and that occurring in more distant matter is to study the iron line variability and profile, as discussed in the next paragraphs.

Recently, collecting data on Seyfert galaxies and Galactic Black hole candidates from different satellites, Zdziarski *et al.* (1999) discovered a significant correlation between the power law index of the primary continuum and the value of the Compton reflection component. This correlation is also present in the BeppoSAX sample of Seyfert galaxies discussed by Matt (2000). There is not much doubt that this correlation is statistically significant. The problem is that it may not be intrinsic, because the two parameters are strongly correlated in the fit procedure: any miscalculation of one of the two parameters immediately gives a (wrong) value of the other parameter (see e.g. the discussion in Vaughan and Edelson, 2000). In other words, the correlation is true if, and only if, all used spectral indices are correctly measured. Given possible misevaluations of this parameter due to complex cold and warm absorptions, the presence of further components like soft excesses, and the fact that the power law is likely only an approximation to the real spectrum, my personal opinion is that the physical reality of this correlation is still to be definitely demonstrated, even if the correlation between slope and iron line flux found by Lubinski and Zdziarski (2000) certainly gives strength to it. In any case, as it potentially conveys important information on the physics and geometry of the X-ray emission, it is worth further exploration.

4.2 Relativistic Iron Lines

Along with the reflection continuum, a prominent iron Kα fluorescent line is also produced in the circumnuclear matter after illumination by the primary continuum. Line variability and profile are fundamental in determining where the line is emitted. Emission from the innermost accretion disc results in a characteristic double horned and skewed line profile due to GR and SR effects (e.g. Fabian *et al.*, 1989; Matt *et al.*, 1992; Martocchia *et al.*, 2000); the line should respond to variations of the illuminating continuum on timescales of a hundred or thousand of seconds at most. If the line originates in distant matter, however, no relativistic effects should be visible, and the time response should occur on scales of months or years.

A typical line profile originating in the innermost regions of the accretion disc is visible in Figure 1. The blue horn is brighter than the red one due to light aberration ('Doppler boosting'), while the red tail is due to the combined effect of gravitational redshift and transverse Doppler. Gravitational light bending contributes to further distortion of the profile at large inclination angles.

The advent, with ASCA, of moderate energy resolution X-ray detectors has permitted observation of the relativistic lines in at least those objects for which the quality of the spectrum was good enough (Tanaka *et al.*, 1995; Nandra *et al.*, 1999). The analysis of a large sample of Seyferts seems to indicate that the relativistic line is quite common (Nandra *et al.*, 1997). For the best known case, MCG-6-30-15, *BeppoSAX* (Guainazzi *et al.*, 1999) and, more recently, *XMM* (Molendi *et al.*, 2000) observations confirmed the presence of a relativistic iron line.

In principle, adopting a reverberation technique similar to that commonly adopted for the optical broad lines, it is possible to measure the black hole mass (Stella, 1990; Matt and Perola, 1992; Reynolds *et al.*, 1999). It is a very difficult technique, which needs long observations of bright sources with very sensitive instruments. Hopefully *XMM-Newton*, and certainly *Constellation-X*, will be able to perform such observations for at least the few brightest objects.

4.3 Iron Lines from Distant Matter

Standard unification models for Seyfert galaxies (e.g. Antonucci, 1993) predict that every Seyfert nucleus is surrounded by cold, thick matter (the 'torus') which, for certain aspect angles, prevents a direct view of the nuclear regions (in this case we have type 2 objects). Even for type 1 objects, for which the nucleus is directly visible, the torus may manifest itself by reflecting a fraction of the primary X-rays, giving rise to a Compton reflection component and a narrow (i.e. unresolvable by present detectors) iron line.

With instruments with only moderate energy resolution it is difficult to disentangle the narrow component from the broad, relativistic one. The best way to search for lines emitted by distant matter is therefore to look for a delayed response to variations of the primary continuum. For instance, in NGC 4151 the line flux was the same when observed by *BeppoSAX* a few months apart, despite large continuum flux variations (Piro *et al.*, 1999). An even more spectacular case is NGC 4051, which was observed by *BeppoSAX* during a prolonged low state (Uttley *et al.*, 1999). The spectrum presented only the reflection component, including a prominent and narrow iron line (Guainazzi *et al.*, 1998). Clearly, this reflection spectrum should have been emitted by matter located at a distance from the nucleus of at least a few light-months, which is the probable distance of the inner surface of the torus, at least for low luminosity AGNs like NGC 4051 (see Bianchi *et al.*, 2000 for the case of the Circinus Galaxy).

The advent of high resolution detectors, like the transmission gratings onboard *Chandra*, has permitted a start to the search for narrow lines directly in the spectrum. For instance, in NGC 5548 an iron line still resolved but not broad enough to have originated in the innermost accretion disc has been discovered (Yaqoob *et al.*, 2000). The most likely origin for this line is the Broad Line Region. The iron line in Circinus (Sambruna *et al.*, 2000), instead, is unresolved and most likely comes from the inner wall of the torus, as originally proposed by Matt *et al.* (1996).

5 NARROW LINE SEYFERT 1s

Narrow Line Seyfert 1 galaxies (NLSy1) were introduced as a subclass by Osterbrock and Pogge (1985) and defined as those sources with an optical/UV line spectrum typical of Seyfert 1s, but with narrower lines (FWHM(Hβ) less than 2000 km s^{-1}). The interest in this class was revived in the mid-90' when it was realized, thanks to *ROSAT* observations, that they have distinct X-ray properties (e.g. Boller *et al.*, 1996), most notably a very steep soft X-ray spectrum and large amplitude variability on relatively short time scales. Later on, *ASCA* (Brandt *et al.*, 1997) and *BeppoSAX* (Comastri *et al.*, 2000) observations revealed that their hard X-ray spectrum is also steeper than in classical, Broad Lines Seyfert 1s.

There are many observational arguments pointing towards a high accretion rate as the main parameter behind the NLSy1 phenomenon. Recently, Nicastro (2000) proposed a model in which it is assumed that the Broad Line Regions arise from instabilities in the accretion disc, occurring when the radiation pressure starts dominating over the gas pressure. As the transition radius between these two regimes increases with the accretion rate, and assuming that the BLR clouds velocity is basically the Keplerian one at the instability radius, an anticorrelation between $\dot{m}$ and line width is expected.

In many objects a deficit of photons around 1 keV is observed. There are several possible explanations for that: blueshifted oxygen edges (Leighly, 1999), ionized discs (Vaughan *et al.*, 1999) or an iron L resonant lines forest (Nicastro *et al.*, 1999). *Chandra* and *XMM-Newton* high energy resolution observations will likely decide which among the above explanations (if any) is the correct one.

6 ABSORPTION. THE UNIFICATION MODEL AND BEYOND

The unification model for Seyfert galaxies assumes that the nucleus in type 2 sources is obscured by circumnuclear matter, the so-called 'torus' (as this matter should have more or less this form, to permit radiation escaping in a funnel as required to explain the ionization cones). The strongest confirmation of the unification model comes from X-rays, as any Seyfert 2 galaxy observed in this band presents evidence for a type 1-like nucleus observed through absorbing matter significantly in excess of that of the Galaxy. Sometimes, like in the case of the archetypal Seyfert 2 galaxy, NGC 1068, the matter is so thick that the nucleus cannot be visible even in hard X-rays (Matt *et al.*, 1997). In these cases, evidence for nuclear emission is indirect, and is provided by reflection components from the torus itself and/or ionized circumnuclear material.

The distribution of absorbing column densities has been studied by Maiolino *et al.* (1998) and Risaliti *et al.* (1999). They found that about half of the sources are 'Compton-thick', i.e. with a column density larger than $\sigma_T^{-1} = 1.5 \times 10^{24}$ cm^{-2}. Interestingly, there is a difference in the distribution of 'strict' Seyfert 2 galaxies and of intermediate Seyferts, the former showing a larger column density than the latter. Matt (2000b) has proposed that the absorber in Seyfert 2s is a Compton-thick and compact 'torus', while the absorber of intermediate objects should be identified with the (Compton-thin) dust lanes observed by *HST* in practically all Seyferts (Malkan *et al.*, 1998).

Recent X-ray observations are also showing that the type 1/type 2 dichotomy, based on optical criteria, is clearly inadequate to describe the variety of observed behaviours. An example is NGC 6240, which *BeppoSAX* discovered to host a high luminosity AGN obscured by a $\sim 2 \times 10^{24}$ cm^{-2} absorber (Vignati *et al.*, 1999). In the optical, this source is classified as a LINER, and IR diagnostics suggest a starburst dominated source, while the AGN luminosity inferred from hard X-rays implies that it is actually the AGN which dominates the energy output. An even more dramatic example is NGC 4945, in which there is no evidence for an AGN till about 10 keV, where finally the nucleus starts piercing through a thick absorber (Iwasawa *et al.*, 1993; Done *et al.*, 1996; Guainazzi *et al.*, 2000). It is clear, therefore, that while any type 2 object appears as an obscured AGN in the X-ray band, the opposite is not true. This is not surprising, after all, because the presence of BLR and NLR are sufficient but not necessary to indicate an AGN (as BL Lac demonstrates), while X-ray emission is a much more fundamental property.

Many more examples came from recent medium to deep *Chandra* surveys (e.g. Mushotzky *et al.*, 2000; Fiore *et al.*, 2000). For instance, the P3 source in the Fiore *et al.* (2000) sample has a luminosity close to 10^{43} erg s^{-1}, largely in excess of that of a normal galaxy, but in the optical there is no evidence whatsoever of nuclear activity. The rather large Calcium break argues against a BL Lac hypothesis. Whether the lack of activity in the optical is due to heavy obscuration or a fueling mechanism strongly favouring X-rays, like an ADAF, is a question which requires deeper X-ray observations as well as observations at IR and radio wavelengths.

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