Part 3

X-ray Surveys for AGN

Wolfgang Voges and Friends

The 2.2m Telescope Dome

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The Obscured AGN Population Probed by X-ray Observations

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Abstract. X-ray properties of obscured AGN are reviewd and recent results obtained from ASCA, BeppoSAX, and Chandra are presented. There is a population of AGN that can only be revealed by hard X-ray observations. Studies of the X-ray background suggest that obscured AGN should significantly outnumber their unobscured counterparts.

1. X-ray Spectra of Obscured AGN

1.1. Effects of X-ray Absorption

The energy distribution of AGN can be approximated by a power-law and is roughly flat over the X-ray band. However, we now know at least in well-studied bright Seyfert galaxies that there are a significant excess of soft X-ray (below half keV) emission and a roll-over of the hard X-ray continuum at a few hundred keV. The soft X-ray excess is believed to be related to the accretion disk while the high energy roll-over is probably due to a cut-off in energy of thermal electrons in a corona which Comptonizes the disk emission into the power-law continuum. There are other subtle spectral distortions due to reflection off the accretion disk surface. These phenomena are likely happening in a region within 100 gravitational radii of a central black hole.

When cold matter lies in the line of sight at radii much further out, a series of photoelectric edges of various elements as well as Hydrogen are imposed on the X-ray continuum and make a low energy cut-off. The energy of the absorption cut-off increases as the column density of the absorbing matter increases. Therefore, going up across the X-ray energy band has the same effect as increasing wavelength in the optical/near-infrared for obscured objects. Assuming the Galactic dust to gas ratio, the optical depth which a near-infrared observation (say, in the K band) can probe is equivalent to that at 2–3 keV. For example, ROSAT, whose bandpass was up to 2 keV, was sensitive to relatively unobscured AGN but no longer sensitive when an absorption column density exceeds 10^{22}cm^{-2} (of course, this restriction is relaxed for high redshift objects). X-ray observatories such as ASCA, BeppoSAX, Chandra and XMM-Newton have sensitivity above 2 keV, which enables these satellites to search for highly obscured AGN. It should, however, be noted that simply shifting the energy window to higher energies does not necessarily guarantee detection of more heavily obscured objects, because of a) increasing importance of Compton down-scattering, as explained below; b) approaching the intrinsic spectral roll-over at high energies.

1.2. What Are Compton-Thick Sources?

When a column density of an absorber exceeds $N_{\rm H} = 1.5 \times 10^{24}{\rm cm}^{-2}$, which corresponds to unity in Thomson depth, even high energy photons that have survived photoelectric absorption get scattered by cold electrons more than once in the absorber and lose their energy via Compton down-scattering. Some of these photons enter the photoelectric absorption regime after losing energy and will be absorbed eventually. This is an important effect (see e.g., Wilman & Fabian 1999) and the transmitted continuum is significantly suppressed by that. The suppression by the Compton down-scattering has a geometry dependence, i.e, the smaller the covering fraction of the absorber, the stronger the suppression, and this dependence is as large as a factor of 3 when $N_{\rm H}$ is $\sim 3\times10^{24}{\rm cm}^{-2}$, for instance (see Matt, Pompilio & La Franca 1999 for details). This introduces an uncertainty when estimating the unabsorbed luminosity of a strongly absorbed source. In summary, when an X-ray absorber becomes optically thick to Compton scattering, the transmitted light is observed to be very faint.

At the same time, the energy of the absorption cut-off moves out above 10 keV. Naturally, detection of transmitted X-ray radiation requires high energy X-ray detectors, as opposed to the modern imaging X-ray telescopes of which the highest energy bandpass terminates around 10 keV. The first such object to be found was the nearby infrared galaxy NGC 4945 with Ginga (Iwasawa et al 1993). Subsequently, many more Compton-thick sources have been found with BeppoSAX (e.g, Risaliti, Maiolino & Salvati 1999; Matt et al 2000). In an extreme case, the absorption column is so large that any transmitted component becomes invisible. A classical example is the prototype Seyfert 2 nucleus of NGC1068 (Fig. 1). No absorbed continuum is detected up to 200 keV (Matt et al 1997).

So, how can Compton-thick sources be probed by Chandra or XMM-Newton? As found in optical light, reflected light from a hidden central source could be present below 10 keV, and its X-ray spectrum would exhibit some distinctive signatures such as a very strong iron Kα line. Possible problems are the flux level of this reflected light can be very low and can also be confused with emission not related to the active nucleus, e.g., a circumnuclear starburst (Fig. 2).

The major X-ray reflecting agent is, of course, electrons. However, there are more possibilities to reflect the radiation of a hidden source into the line of sight in X-ray than in optical light. The inner surface of the obscuring matter itself, which is optically thick, can be an X-ray reflector. X-ray reflection from a cold, optically thick medium has been studied well in terms of reflection from an accretion disk (e.g., George & Fabian 1991), and various studies of simulated reflection spectra have been performed in the context of the unified scheme (e.g., Ghisellini et al ; Krolik, Madau & Zycki 1994). The reflection from cold matter is characterized by a very hard continuum and a strong iron K line at 6.4 keV (with EW of $\sim$ 1 keV for solar abundance). Highly (photo-)ionized gas with a much smaller optical depth, sometimes identified with the warm absorbers found in Seyfert 1 galaxies (Krolik & Kriss 2001), can also be an important reflector. In this case, the reflected continuum has a softer spectrum because

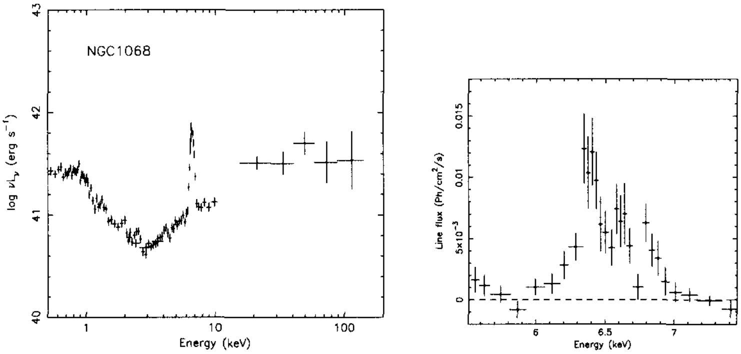

Figure 1. Right panel: The BeppoSAX spectrum of NGC1068. No direct emission from a hidden nucleus is visible up to 200 keV. The spectrum is dominated by reflected light, particularly in the hard X-ray band, reflection from optically thick cold matter produces a very hard spectrum (Matt et al 1997). Right panel: The iron K line complex in NGC1068 observed with the ASCA SIS (Iwasawa, Fabian & Matt 1997).

photoelectric absorption within the reflecting medium is less important at lower energies, and emission lines from ionized atoms are observed. Thus X-rays from a hidden nucleus may contain reflection from matter with a range of ionization. The iron K line complex is the most prominent spectral feature, and usually the 6.4 keV line is the major component of the line complex. This indicates that reflection from cold matter is important and a major component at least at energies around 6 keV. Although the reflected X-ray light may be relatively easy to identify from the spectral signatures, the X-ray flux we can observe is only a small fraction (1 per cent or likely to be much smaller) of a primary source. Combined with the reduced transmitted component due to the high absorption column density, the faint nature of Compton-thick sources makes it difficult to detect them at moderate to high redshift even with the advanced X-ray observatories.

2. What Fraction of AGN is Obscured?

Fig. 3 shows X-ray spectra of the three nearest AGN[1] obtained with BeppoSAX. They are all located within 4 Mpc, all strongly absorbed ($N_H \sim 2 \times 10^{23} cm^{-2}$ for

[1]NGC 4395 is, for example, another AGN at a distance of 2.6 Mpc, but has a much lower luminosity ($3 \times 10^{39} erg\ s^{-1}$)

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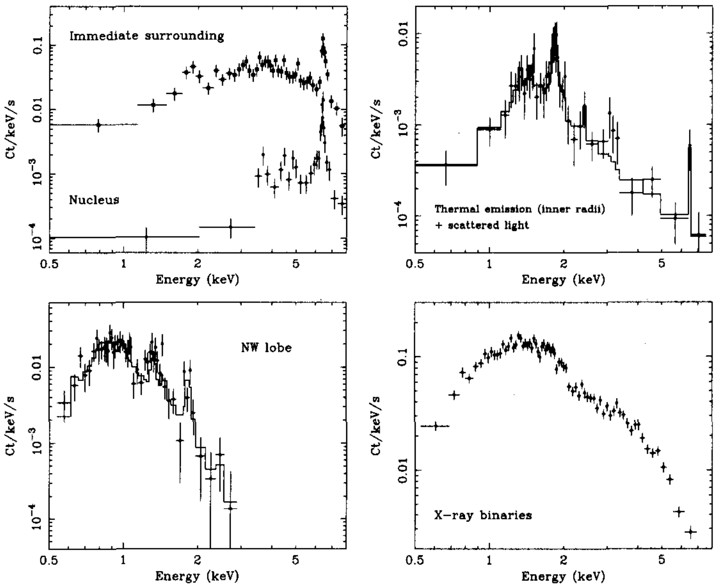

Figure 2. Chandra ACIS-S spectra taken from different areas of the X-ray emitting region of the nearby starburst/Seyfert 2 galaxy, NGC4945. The total X-ray emission from an obscured AGN like this galaxy can consist of the nuclear emission as well as many other components unrelated to the active nucleus. In this example, reflected AGN light from the hidden active nucleus, thermal emission induced by starburst winds extending towards the NW, which shows significant spatial variations, and X-ray binaries scattered across the galaxy are shown to demonstrate the possible complexity in an X-ray spectrum of an obscured AGN. It should be noted that these components cannot be resolved in distant objects.

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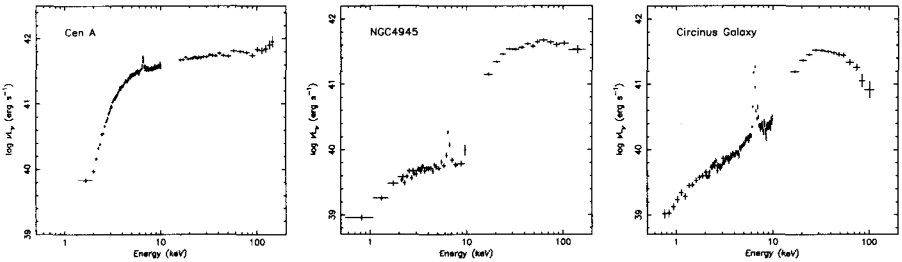

Figure 3. The BeppoSAX spectra of the nearest three AGN, Cen A, NGC 4945 and the Circinus Galaxy. All three X-ray nuclei are strongly absorbed.

Cen A, $3 \times 10^{24}\mathrm{cm}^{-2}$ for the Circinus Galaxy and $5 \times 10^{24}\mathrm{cm}^{-2}$ for NGC 4945) and their absorption-corrected luminosities exceed $5 \times 10^{41}\mathrm{erg\ s}^{-1}$. Suppose our local Universe is representative of the whole Universe. Integrating the 0.5–2 keV ROSAT AGN luminosity function by Miyaji, Hasinger & Schmidt (2000) down to $5 \times 10^{41}\mathrm{erg\ s}^{-1}$ gives a density of 2×10^{-4} Mpc^{-3}. As mentioned above, the ROSAT AGN population are predominantly unobscured AGN. With a correction for local density in a sphere of radius corresponding to $\sim$ 500 km s^{-1} relative to the mean density of the Universe (Schlegel et al 1994), the number of AGN with $L_{\mathrm{x}} \geq 5 \times 10^{41}\mathrm{erg\ s}^{-1}$ within 4 Mpc expected from the soft X-ray AGN luminosity function is then 0.05, 60 times smaller than observed (see Matt et al 2000). This estimate may be too simple but demonstrates that obscured AGN should outnumber their unobscured counterparts significantly.

This argument is supported by studies of the X-ray background (XRB). We now believe that the XRB originates from the integrated X-ray emission of AGN. Modeling of its flat spectrum implies considerable absorption in most AGN (Setti & Woltjer 1989; Madau, Ghisellini & Fabian 1994; Comastri et al 1995; Celotti et al 1995). Suppose the 30 keV peak of the XRB energy distribution is little affected by photoelectric absorption (Compton down-scattering means Compton-thick sources would not have significant contribution at this energy), we estimate 80–90 per cent of the total accretion power in the Universe is absorbed (Fabian & Iwasawa 1999). Correcting for this absorption, using Sołtan's cosmology-free argument, and assuming an accretion efficiency of 0.1 and a mean AGN redshift of 2, the XRB intensity is translated into a mean local density of black holes. The value we obtained is 6×10^5 $M_{\odot}$ Mpc^{-3}, much larger than estimates based on optical quasar counts, but in agreement with recent estimates based on X-ray counts (Salucci et al 1999) and Maggorian et al (1998) results (Haehnelt, Natarajan & Rees 1999). The absorbed accretion power probably emerges in the infrared bands, and also contributes some fraction of the infrared background light (Fixen et al 1998). Obscured AGN found in infrared luminous galaxies are discussed below.

3. X-ray Properties of Luminous Infrared Galaxies

Luminous Infrared Galaxies are found to be X-ray faint both at low and high redshift. Generally, starburst galaxies generate X-ray emission of luminosity 3–4 orders of magnitude below that of infrared emission. Whether the X-ray faintness of these objects is due to lack of active nuclei or heavy obscuration is a subject of debate.

Local Ultra-Luminous Infrared Galaxies (ULIGs) found by the IRAS survey (Soifer et al 1987) are divided into warm and cold objects based on their infrared colours. It has been known through optical spectroscopic surveys that warm IRAS objects tend to host Seyfert nuclei (e.g., De Grijp et al 1985) while cold IRAS objects are usually star-forming galaxies. X-ray observations are in agreement with this tendency: an absorbed X-ray source is often found in warm IRAS objects. However, there are exceptions unique to the X-ray observations. NGC 4945, as mentioned above, hosts a heavily obscured X-ray nucleus, yet this galaxy shows a cold IRAS color and no evidence for an active nucleus in the optical to near-infrared band (e.g., Marconi et al 2000), and the mid-infrared spectrum observed with ISO is typical of a starburst (Genzel et al 1998). A higher luminosity example is NGC 6240 (references for the X-ray observations are Iwasawa & Comastri 1998; Vignati et al 1999; Ikebe et al 2000). These two galaxies exhibit almost identical shapes of spectral energy distributions, albeit nearly two decades apart in luminosity (Fig. 4). These examples demonstrate that X-ray observations sometimes tell a different story from conventional emission-line spectroscopic classification.

Arp 220, the nearest of the ULIGs, however, does not show any AGN signature even in the X-ray band. A BeppoSAX observation failed to detect hard X-ray emission above 10 keV which imposes a rather strict constraint on the presence of an AGN: if this merger system were to host an energetically significant AGN, the absorption column density hiding a central source must exceed $10^{25}\mathrm{cm}^{-2}$ (Iwasawa et al 2001).

Faint SCUBA sources are probably high-redshift analogs to ULIGs. The weak correlation of detection between SCUBA and Chandra (e.g., Fabian et al 2000; Hornschemeier et al 2000; Bautz et al 2000) suggests that the SCUBA sources are similar to Arp 220 in the X-ray band also (see Fig 2 in Fabian et al 2000). Clearly, it is important to identify what powers Arp 220 type objects (estimates of the AGN contribution to the FIR background can be found in Almaini et al 1999 and Risaliti et al 2002).

4. Obscured AGN at High Redshift

As in the case for low redshift objects, galaxies exhibiting evidence for hot dust, which is likely to be heated by AGN radiation, are among the first to be found to harbor an obscured AGN emitting at QSO luminosity. BeppoSAX detected a hard X-ray excess (Franceschini et al 2000) above the previously known cluster emission around IRAS 09104+4109, one of the hyperluminous infrared galaxies at $z = 0.442$ (Kleinmann et al 1988). A follow-up Chandra observation clearly detected a reflection-dominated X-ray nucleus, spatially separated from the surrounding cluster emission (Iwasawa, Fabian & Ettori 2001). This object shows

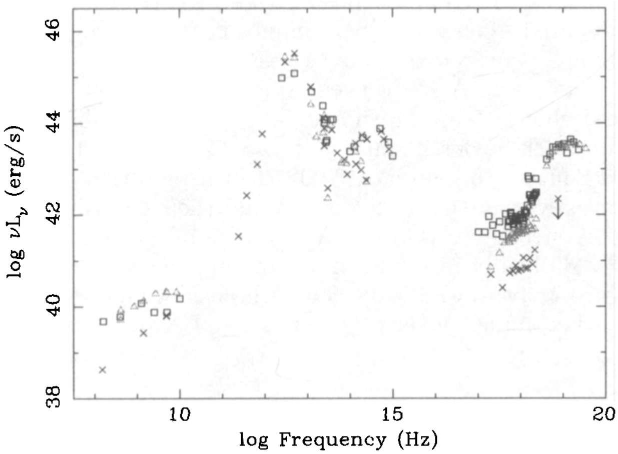

Figure 4. Spectral energy distributions of three infrared galaxies, Arp 220 (crosses), NGC 6240 (squares) and NGC 4945 (triangles). The SED of NGC 4945 has been mutiplied by 80 to match the far-infrared peak of Arp 220. NGC 4945 and NGC 6240 harbor heavily obscured active nuclei, which can only revealed in the hard X-ray band, and show almost identical SEDs. Note that Arp 220 shows considerably fainter X-ray emission compared with the other two.

a very warm IRAS color and is not detected with SCUBA at 850 μm (Deane & Trentham 2002), which indicates the lack of cool ($T \sim 40$ K) dust as seen in local ULIGs. Similarly, the two Chandra sources detected serendipitously in the field of the cluster Abell 2390 (with the aid of the lensing magnification of the cluster gravitational potential) have no SCUBA counterparts but are identified with ISOCAM 6.7 and 15 μm sources (Lémonon et al 1998; Altieri et al 1999). A broad-band study suggests that these X-ray sources are obscured AGN with hot dust at redshifts of 0.85 and 2.8 (Wilman, Fabian & Gandhi 2001). Objects similar to these at high redshift appear to make a significant contribution to the cosmic background radiation at 60 μm, while dusty star-forming galaxies as found with SCUBA could account for all the background radiation at longer wavelengths (Blain & Phillips 2002).

Recent deep Chandra surveys have resolved most of the XRB (Mushotzky et al 2000; Brandt et al 2001; Giacconi et al 2001). The log N–log S plot obtained from these surveys shows flattening of the slope for 2–10 keV sources below a flux level of 10^{-14}erg s^{-1}cm^{-2}. This means that X-ray sources at that flux level are the majority of those composing the XRB. A serendipitous source survey

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was conducted using various Chandra observations (mainly of clusters), aiming at detection of these X-ray sources, because the flux range can be reached with a moderate amount of Chandra exposure (30–40 ks). This survey has found several more obscured AGN with QSO luminosity (Crawford et al 2001; Gandhi et al 2002). An important remark about these sources is that some of them show no optical signature of an AGN or even no emission lines at all, particularly in heavily obscured objects (e.g., Mushotzky et al 2000; Gandhi et al 2002).

A Compton-thick Seyfert 2 galaxy at $z = 3.7$ has been found in the Chandra Deep Field South (Norman et al 2002). Such reflection-dominated sources appear to be rare even in the deep surveys and their contribution to the XRB may be small. A strongly absorbed ($N_H \sim 10^{23}$cm^{-2}), powerful X-ray source $L_X \sim 10^{45}$ erg s^{-1}) has been found in a radio galaxy B2 0902+343 at $z = 3.4$ (Fabian Crawford & Iwasawa 2002). Thus the list of highly obscured AGN at high redshift is becoming longer as Chandra and XMM-Newton observations increase.

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