X-RAYS FROM THE ENVIRONMENT OF SUPERMASSIVE BLACK HOLES IN ACTIVE GALAXIES

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X-rays are a powerful probe of the physical conditions in the nuclei of active galaxies (AGN). We review the X-ray properties of radio-quiet AGN, LINERs and ULIRGs based on observations carried out with the X-ray satellite ROSAT. We then summarize the observations of giant X-ray flares from non-active galaxies, interpreted as stellar tidal disruptions by supermassive black holes.

1 Introduction

Active galaxies (AGN) are believed to be powered by accretion onto supermassive black holes at their centers. X-ray observations currently provide the most powerful way to explore the black hole region of AGN. The bulk energy output of active galactic nuclei is in the X-ray bandpass, and the X-ray properties of AGN, particularly their high luminosity and rapid variability, originally gave the best evidence that supermassive black holes (SMBHs hereafter) do reside at the centers of AGN.

Below, we first summarize the results of X-ray observations of radio-quiet AGN, LINERs and ultraluminous IR galaxies carried out with the ROSAT (Trümper 1983) X-ray observatory. We then address the X-ray search for SMBHs in non-active galaxies.

2 Active Galactic Nuclei (AGN)

In the course of the ROSAT all-sky survey (Voges et al. 1996), many new AGN have been identified, confirming that X-ray surveys are very efficient in finding new AGN, and many have been studied in detail in the later phase of pointed observations on selected bright targets. Large-sample studies of radio-quiet quasars gave a mean powerlaw photon index $\Gamma_x \simeq -2.5$ and indicated a flattening of the X-ray spectrum with increasing energy/redshift, interpreted as the onset of a new spectral component (e.g., Schartel et al. 1996a,b, Ciliegi & Maccacaro 1996, Yuan et al. 1998). A large sample study of Seyfert galaxies observed during the ROSAT all-sky survey showed the spectra to span a range in powerlaw indices between $\Gamma_x = -1.6... - 3.4$ (Walter & Fink 1993). Many spectra of Seyfert galaxies show complexity in form of soft excesses or ionized absorbers.

X-rays at the centers of AGN originate in the accretion-disk region (see Mushotzky et al. 1993, Collin et al. 2000 for reviews). On larger scales, but still within the nucleus, X-rays might be emitted by a hot intercloud medium at distances of the broad or narrow-line region, BLR or NLR (e.g., Elvis et al. 1990;
Ogle et al. 2000).

The X-rays which originate from the accretion-disk region are reprocessed in form of absorption and partial re-emission (e.g., Netzer 1993, 1996, Krolik & Kriss 1995) as they make their way out of the nucleus. The reprocessing bears the disadvantage of veiling the intrinsic X-ray spectral shape, and the spectral disentanglement of many different potentially contributing components is not always easy. However, reprocessing also offers the unique chance to study the physical conditions and dynamical states of the reprocessing material, like: the ionized absorber; the torus, which plays an important role in AGN unification schemes (Antonucci 1993, see also Elvis 2000); and also the BLR and NLR. Detailed modeling of the reprocessor(s) is also necessary to recover the shape and properties of the intrinsic X-ray spectrum. In the soft X-ray bandpass, the best-studied reprocessor so far is the so-called ‘warm absorber’, highly ionized gas in the circum-nuclear environment. This is because it is nearly completely ionized in Hydrogen and Helium, and does not absorb at very soft energies, like torus, BLR and NLR will, if they are located along the line-of-sight.

With ROSAT, the signatures of a warm absorber, absorption edges of highly ionized oxygen ions at $E_{\text{OVII}} = 0.74$ keV and $E_{\text{OVII}} = 0.87$ keV, were first detected in MCG-6-30-15 (Nandra & Pounds 1992). Detailed studies of many other AGN followed, with the following results (see Komossa 1999 for a review on warm absorbers):

Ionized absorbers are observed in $\sim$50% of the well-studied Seyfert galaxies, they are less abundant in quasars (e.g., Ulrich & Molendi 1996, Laor et al. 1997), but do occur in some. In many Seyfert galaxies, warm absorbers replaced the soft excess, i.e., steep X-ray spectra in the soft X-ray band, originally thought to stem from black-body-like soft excess emission turned out to be caused by the presence of warm absorbers.

From the general lack of rapid variability in response to intrinsic luminosity variations, low densities of the absorbers were generally inferred. For example, the limits on density and location of the ionized material in NGC 4051 are $n_H \lesssim 3 \times 10^7$ cm$^{-3}$ and $r \gtrsim 3 \times 10^{16}$ cm, its column density is $N_w \simeq 10^{22.7}$ cm$^{-2}$, and its electron temperature is a few $10^5$ K (Komossa & Fink 1997a). Several approaches were made to assess the thermal stability of the warm absorber in the context of multi-phase cloud equilibrium models (e.g. Reynolds & Fabian 1995, Komossa & Fink 1997a,b), addressing the possibility that the ionized material is in equilibrium with a hotter (or cooler) gas phase. Results are summarized in Fig. 1.

Whereas the existence of warm absorbers was first deduced from X-ray spectra, there is now evidence that the same material also shows up in other spectral bands, and the multi-wavelength approach is a powerful one. There is good evidence that the dust which causes the optical reddening of several AGN is mixed with the ionized absorber (Komossa & Bade 1998 and references therein; see Tab. 1 of Komossa 1999 for a list of dusty warm absorbers). Further, several AGN have

e.g., MCG-6-30-15, Nandra & Pounds 1992; NGC 3783, Turner et al. 1993; NGC 3848, Nandra et al. 1993; NGC 4051, Pounds et al. 1994; NGC 3227, Komossa & Fink 1997b; a more complete list of objects including observations from other X-ray satellites is given by Komossa (1999)

e.g., 3C351, Fiore et al. 1993; 3C212, Mathur 1994; MR 2251-178, Komossa 2001
Figure 1. Equilibrium gas temperature $T$ versus pressure ($U/T$, where $U$ is the ionization parameter), and locations of selected warm absorbers. Regions where $T$ is multi-valued for constant $U/T$ and where the gradient of the equilibrium curve is positive allow for the co-existence of several phases in pressure balance. The equilibrium curves are shown for different ionizing continua and gas properties, and the locations of several warm absorbers are marked. **Upper panel:** The solid lines correspond to spectral energy distributions (SEDs) with (i) $\Gamma_x = -1.6$ (left) and (ii) $\Gamma_x = -1.9$ (right), and $\alpha_{\text{uv}} = -1.4$. The symbols mark the locations of warm absorbers, derived from X-ray spectral fits. Filled square: Mrk 1298; star: RXJ 0134-4258; arrow: MCG-6-30-15 (Reynolds & Fabian 1995); triangles: PG 1404+226 high- and low-state; circles: PKS 2351-154 high- and low-state. **Lower panel:** curves (i) and (ii) from the upper panel are re-drawn. The dashed line corresponds to an input SED with $\Gamma_x = -1.9$ but instead of solar gas abundances we adopted depleted metal abundances and mixed dust with the gas (see Komossa & Fink 1997b for details); the dotted line corresponds to the observed SED of NGC 4051 (Komossa & Fink 1997a) with $\Gamma_x = -2.3$. Filled triangle: location of the dusty warm absorber of NGC 3227; open square: dusty warm absorber of NGC 3786, lozenges: NGC 4051 during the Nov. 1993 (upper lozenge) and Nov. 1991 (lower lozenge) observation.
been presented where UV- and X-ray warm absorber are likely one and the same component, or are related to each other (e.g., Mathur 1997 and references therein).

Finally, warm absorbers have been invoked to explain some otherwise puzzling observations like the dramatic spectral variability of the Narrow-line Seyfert 1 galaxy RXJ0134-4258 (Komossa & Meerschweinchen 2000), or the apparent huge excess cold X-ray absorption in high-redshift quasars (Schartel et al. 1997, Fabian et al. 2001).

Absorption features at \( \sim 1.1 \) keV (e.g., Ulrich & Molendi 1996) have been interpreted in terms of relativistic outflow of the ionized medium (Leighly et al. 1997, see also Brandt et al. 1994), but several alternative explanations – most of them still linked to a warm absorber albeit in a different way – have been suggested (e.g., Ulrich et al. 1999, Nicastro et al. 1999, Turner et al. 1999).

Recent Chandra observations of the Seyfert galaxies NGC 5548 and NGC 3783 revealed a rich absorption line spectrum (Kaastra et al. 2000, Kaspi et al. 2000) and demonstrate the power of high-resolution spectroscopy to probe the physics of the ionized gas in the nuclei of AGN.

In summary, the study of the ionized absorbers provides a wealth of information about the nature of the warm absorber itself, its relation to other components of the active nucleus, and the intrinsic AGN X-ray spectral shape, and leads to a better understanding of the black hole region of AGN, and its cosmic evolution.

3 LINER galaxies

LINER (Low-Ionization Nuclear Emission-Line Region) galaxies are characterized by their optical emission line spectrum which shows a lower degree of ionization than AGN (Heckman 1980). Their major power source and line excitation mechanism have been a subject of lively debate ever since their discovery. LINERs manifest the most common type of activity in the local universe. If powered by accretion, they probably represent the low-luminosity end of the quasar phenomenon, and their presence has relevance to, e.g., the evolution of quasars, the faint end of the Seyfert luminosity function, the soft X-ray background, and the presence of SMBHs in nearby galaxies.

The soft X-ray properties of LINERs are inhomogeneous (Komossa et al. 1999, and references therein). Whereas the spectra of about 50% of them are best described by AGN-like powerlaws, the others are dominated by thermal Raymond-Smith emission with evidence that the spectra are more complex than emission from single-temperature gas in collisional-ionization equilibrium. X-ray luminosities are in the range \( \sim 10^{38} \text{--} 41 \) erg/s (for comparison: Seyfert 1 galaxies and quasars typically exceed \( 10^{42} \) erg/s). The general absence of short-time scale (hours-weeks) variability is consistent with the suggestion that LINERs accrete in the advection-dominated mode (e.g, Yi & Boughn 1998, 1999, and references therein).

4 Ultraluminous Infrared galaxies (ULIRGs)

ULIRGs, characterized by their huge power-output in the infrared which exceeds \( 10^{12} L_\odot \) (Sanders & Mirabel 1996), are powered by massive starbursts or SMBHs.
The discussion, which one actually dominates received a lot of attention in recent years (e.g., Joseph 1999, Sanders 1999).

Many distant SCUBA sources, massive and dusty galaxies, are ULIRG equivalents at high redshift. Local ULIRGs are ideal laboratories to study the physics of galaxy formation and the processes of IGM enrichment (e.g., Heckman 1999), and the physics of superwinds (Breitschwerdt & Komossa 2000 and references therein) driven by the nuclear starbursts.

With a redshift $z = 0.024$ and a far-infrared luminosity of $\sim 10^{12} L_\odot$, NGC 6240 is one of the nearest members of the class of ULIRGs. Whereas X-rays from distant Hyperluminous IR galaxies, HyLIRGs, were not detected by Wilman et al. (1999), and the ULIRGs in the study of Rigopoulou et al. (1996) were X-ray weak, NGC 6240 turned out to be exceptionally X-ray luminous. It is the most luminous emitter in extended soft X-rays among ULIRGs (Komossa et al. 1998). Starburst-driven superwinds are the most likely interpretation of the extended emission (see Schulz & Komossa 1999 for alternatives), albeit being pushed to their limits to explain the huge power output (Schulz et al. 1998).
5 X-ray search for SMBHs in non-active galaxies

Do SMBHs exist at the centers of all galaxies? This question is relevant for, e.g., the study of the formation and evolution of galaxies and AGN in general (see Kormendy & Richstone 1995, Schulz & Komossa 1999 for reviews).

One efficient method to search for such usually quiescent SMBHs in nearby, non-active galaxies is to make use of the expected flares from tidally disrupted stars (e.g., Lidskii & Ozernoi 1979, Rees 1988, 1989), and the first excellent candidates for tidal disruption events in optically non-active galaxies have been discovered in the last few years (e.g., Bade et al. 1996, Komossa & Bade 1999). Depending on its orbits, a star approaching a SMBH will be tidally disrupted if

$$r_t \approx r_*(\frac{M_{BH}}{M_*})^{\frac{1}{3}},$$

where $r_t$ is the tidal radius, and $M_{BH}$ the black hole mass. The star is first heavily distorted, then disrupted. About half of the gaseous debris will be unbound and gets lost from the system (Young et al. 1977). The rest will be eventually accreted by the black hole (Cannizzo et al. 1990, Loeb & Ulmer 1997). The debris, first spread over a number of orbits, quickly circularizes (Rees 1988, Cannizzo et al. 1990) due to the action of strong shocks when the most tightly bound debris interacts with other parts of the stream (Kim et al. 1999). The process is accompanied by a flare of electromagnetic radiation with the maximum in the UV or EUV spectral region, and with a duration of months to years.

The giant-amplitude X-ray outbursts which have recently been discovered with ROSAT from several non-active galaxies were interpreted in terms of such tidal disruption events (e.g., Bade et al. 1996, Komossa & Bade 1999, Komossa & Greiner 1999). The X-ray emission of these galaxies varied by up to a factor $\sim$200 (NGC 5905) and they reached X-ray luminosities as large as $10^{44}$ erg/s (RXJ1242-1119); a summary of the observations is given in Table 1.

These flares enable us to investigate the very vicinity of the SMBH. Increased sensitivity of future X-ray instruments will allow to follow the disruption and accretion process in detail, and study the strongly relativistic effects related to them (e.g., they depend on relativistic precession effects around the Kerr metric).

Table 1. Summary of the X-ray properties of NGC 5905 and RX J1242–1119 during outburst. $L_x$ gives the intrinsic luminosity in the (0.1–2.4) keV band using $H_0 = 50$ km/s/Mpc, $T_{bb}$ is the black body temperature derived from a black body fit to the data.

| name          | redshift | $kT_{bb}$ [keV] | $L_{x,bb}$ [erg/s] | references             |
|---------------|----------|----------------|-------------------|------------------------|
| NGC 5905      | 0.011    | 0.06±0.01      | $3 \times 10^{42}$ | Bade et al. 1996, Komossa & Bade 1999 |
| RX J1242–11   | 0.050    | 0.06±0.01      | $9 \times 10^{43}$ | Komossa & Greiner 1999 |

* Mean luminosity during the outburst; since the flux varied by a factor $\sim$3 during the observation, the peak luminosity is higher.
Figure 3. Optical image of NGC 5905 and error circle of the X-ray outburst emission (taken from Bade et al. 1996).

Figure 4. Long-term X-ray lightcurve of NGC 5905 (taken from Komossa & Bade 1999).
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