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Exploring the range of black hole masses with Chandra

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Abstract. Efficiently accreting super-massive black holes (SMBHs) in active galactic nuclei (AGNs, with masses in excess of 10^6 M$\odot$) and black holes in Galactic X-ray binaries (with masses $\sim$ 10 M$\odot$, e.g., see Tanaka & Lewin 1995) have long been studied in X-rays. AGNs and black hole X-ray binaries are luminous and fairly common X-ray sources that have been successfully observed with many X-ray observatories, since the beginning of X-ray astronomy nearly four decades ago. The study of black holes in X-rays has now acquired new dimensions thanks to the sub-arcsecond resolution, sensitive observations of the *Chandra* X-ray Observatory. In this paper I address two new lines of investigation that have been blossoming thanks to *Chandra*: quiescent galactic nuclei (QGNs) associated with SMBHs, and the hunt for intermediate mass black holes (IMBHs).

Key words. Galaxy: active – Cosmology: observations

1. Low-luminosity and Quiescent SMBHs

It is now well known that SMBHs are ubiquitous in large galactic bulges, with masses that scale proportionally to the bulge luminosity and velocity dispersion (Gebhardt et al 2000; Ferrarese & Merrit, 2000). However, only a few percent of these SMBHs are X-ray luminous AGNs. This is puzzling, because these nuclei are surrounded by hot ISM in elliptical galaxies, which in principle should provide a ready fuel supply for the SMBH (Bondi 1952). As first pointed out by Fabian & Canizares (1988), the expected Bondi accretion rates should imply readily detectable X-ray luminosities in elliptical galaxies with hot gaseous halos, which are however not detected. Below we discuss recent results on low-luminosity AGNs (sources for which optical spectra, e.g. Ho et al . 1997, or radio emission and jets suggest some nuclear activity), and QGNs, where no activity has been detected to very low limits (Ho 2002).

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1.1. X-ray observations of low-luminosity AGNs

A growing body of literature discusses the X-ray properties of low luminosity AGNs and QGNs. Perhaps the first paper on this subject regarded the detection of a low-luminosity nuclear source in the Sombrero galaxy with ROSAT (Fabbiano & Juda 1997; $L_X \sim 9 \times 10^{39}$ erg s^{-1}), later confirmed with *Chandra* and XMM-*Newton* (Pellegrini et al 2003a). Other low-luminosity nuclei include IC1459 (Fabbiano et al 2003), where a luminosity of 7.6×10^{40} erg s^{-1}s is associated with a 2 ×

10^9 M$\odot$ SMBH; NGC1316 (the radio galaxy Fornax A) with a nuclear luminosity of 4.7×10^{39} erg s^{-1} (Kim & Fabbiano 2003); and IC4296 (Pellegrini et al 2003b), with $L_X \sim 2.4 \times 10^{41}$ erg s^{-1}. These luminosities are significantly sub-Eddington, given the mass of the SMBHs ($L_X/L_{Edd} \sim 10^{-6} - 10{-}7$). All these sources tend to have 'normal' AGN type X-ray spectra (power-law with photon index of $\sim$1.8). Stringent limits on the detection of Fe-K 6.4 keV emission line (at least for IC1459, Fabbiano et al 2003), exclude that the low luminosity is due to absorbed Compton-thick emission. Similarly, no indication of exceptionally high absorption was found in a survey 41 low-luminosity AGN with *Chandra* (Ho et al 2001), detected with luminosities in the $10^{38} - 1041$ erg s^{-1} range. Given the constraints on the Bondi accretion rate, derived from the estimate of the density and temperatures of the surrounding hot ISM, these sources are several orders of magnitude fainter that what would be predicted from efficient emission at the Bondi rate. While the X-ray luminosity could be explained by inefficient advection-dominated accretion flows (ADAF), in some cases at least (e.g., IC1459, IC4296; Fabbiano et al 2003, Pellegrini et al 2003b) the radio-to-X-rays spectral energy distribution cannot be reconciled with these models, so that jet models have also been proposed (see also DiMatteo et al 2003 for M87).

1.2. *Chandra* observations of QGNs

Louis Ho (2002) pioneered the study of nearby QGNs with optical spectroscopy. With *Chandra* we can detect sources as faint as a few 10^{37} erg s^{-1} (the luminosity of an X-ray binary) in a large number of galaxies. Observations of QGNs with measured SMBH mass have pushed nuclear X-ray luminosities to very low values: $< 2 \times 10^{38}$ erg s^{-1} for a point source emission in NGC821 (Fabbiano et al 2004), and $\sim 10^{38} - 1039$ erg s^{-1} for five additional QGNs chosen from the sample of Ho (2002) on the basis of their lack of optical emission lines and radio emission (Soria et al 2006a). These luminosities are comparable to the emission of a luminous X-ray binary and so, even in the case of detections, may be upper limits to the true luminosity of the QGN.

Some of the faintest QGNs do not have a detectable point source at the position of the nucleus. Extended emission has been reported in NGC821 (Fabbiano et al 2004; where a possible jet-like feature has been suggested) and in other four QGNs (NGC3377, NGC4564, NGC4697 and NGC 5845, Soria et al 2006a). Given the low-luminosities of these QGNs, it is possible that part of this diffuse emission is the result of confusion with X-ray binaries in the parent galaxy. The spectra tend to be harder than that of the typical emission of the hot ISM of early-type galaxies, suggesting either nuclear-related emission or X-ray binary contamination.

1.3. Accretion and emission scenarios

With *Chandra* we can also detect the soft (kT$\sim$0.3 keV) X-ray emission of the circum-nuclear hot ISM, and thus constrain the Bondi accretion rate. Silvia Pellegrini (2005) compiled from the literature a sample of $\sim$50 low-luminosity AGNs and QGNs with measured SMBH mass, nuclear LX, and circum-nuclear hot gas densities and temperatures. She finds that the X-ray luminosity varies by $\sim$3 orders of magnitude and is neither correlated with the mass of the SMBH nor with the Bondi accretion rate. Moreover, the nuclear L_X is always less than predicted on the basis of standard high radiative efficiency models, but is in general larger than predicted by ADAF models, unless outflows and convections reduce the accretion flow. Pellegrini argues that the lack of any dependence of LX on accretion rate and SMBH mass is best explained if there is feedback from the SMBH accretion in the surrounding hot ISM (e.g. Binney & Tabor 1995; Ciotti & Ostriker 2001). The possibility of feedback is supported by symmetric sharp hot features discovered with *Chandra* in the hot ISM of the QGN of NGC4636, which could be explained as the result of a nuclear outburst (Jones et al 2003). Moreover, feedback would remove unaccreted gas from the circum-nuclear region.

Soria et al (2006a, b) build on these considerations in their study of six extreme QGNs. In particular, they find that these QGN are overluminous in X-rays if compared with the Pellegrini (2005) sample, emitting in excess of standard ADAF prediction, for a Bondi accretion rate estimated on the basis of the hot ISM. Following the suggestion of Pellegrini (2005) and Fabbiano et al (2004), they consider outgassing from normal stellar evolution as an additional fuel supply for the SMBH. Estimates based on the inner profiles of the stellar surface brightness from archival HST data support this picture. Soria et al (2006b) discuss the conditions for mass equilibrium inside the sphere of influence of a SMBH, so that the total gas injection is balanced by accretion across the event horizon plus outflows. A fraction of the total accretion power would be sufficient to sustain a self-regulating outflow that removes from the circum-nuclear region the gas that does not sink into the SMBH. The rest of the accretion power may be carried out in a jet or advected. But other scenarios are possible: for example incoming gas may form stars (Tan & Blackman 2005); Spitzer observations will soon provide constraints on this possibility.

2. Do we detect Intermediate Mass Black Holes?

Until recently, the dynamical signature of black holes has been found in two different mass ranges: the super-massive black holes ($\sim 10^{9-7}$ M$\odot$) discussed above, and stellar black holes in Galactic X-ray binaries. Recently, nuclear black hole masses have been measured in low-luminosity AGNs (Barth, Greene & Ho 2005), extending the detected black hole mass range down to $\sim 10^4$ M$\odot$. But still a gap in the range of black hole masses remains. Of particular interest are the so-called IMBHs, with masses of $\sim 50 - 10^4$ M$\odot$. This mass range bridges the masses expected from black holes resulting from the evolution of normal massive stars (up to ~ 30 M$\odot$, Belczynski, Sadowski & Rasio 2003), and more massive black holes that may result from either core collapse in globular clusters (e.g., Bahcall & Ostriker 1975; Portegies Zwart et al 1999; Gurkan, Freitag & Rasio 2004) or from the collapse of primordial metal free very massive stars (e.g., Madau & Rees 2001; Volonteri, Haardt & Madau 2003; Islam, Taylor & Silk 2003; Volonteri & Perna 2005).

A class of X-ray sources (the Ultra-Luminous X-ray Sources, ULXs) discovered with the Einstein Observatory, has been proposed as a candidate for this type of black hole (Long & Van Speybroeck 1983, see Fabbiano 1989; Colbert & Ptak 2002). These sources are rare non-nuclear sources found in galaxies, with luminosities in the range of 10^{39-41} erg s^{-1}. With *Chandra*, these sources can be easily resolved in galaxies as distant as ~ 30 Mpc, resulting in a significant sample for study. We now know that ULXs are associated with intensely star forming galaxies, rather than ellipticals (e.g. Swartz et al 2004). The discovery of a rich population of ULXs (Fabbiano et al 2003a, 2004a) in the merging galaxy pair NGC4038/9 (the Antennae) prompted the suggestion that these sources may be normal X-ray binaries in a particularly high accretion rate state of their evolution, emitting collimated beams of radiation (King et al 2001; see also Rappaport et al 2005 for evolutionary calculations). Alternatively, super-Eddington accretion disks (Begelman 2002) could explain most ULX luminosities. Relativistic jets, as in Doppler-beamed microquasars (Koerding, Falke & Markoff 2002) have also been proposed. Other models have also been advanced (very young SNRs, e.g. Fabian & Terlevich 1996; young Crab-like pulsars, Perna & Stella 2004), but cannot explain the bulk of the ULXs, given their spectral and time variability characteristics that point to binary accretion systems (see e.g. Fabbiano et al 2003b).

Given these exciting and diverse possibilities it is not surprising that ULXs have generated a large amount of both observational and theoretical work. Among the recent reviews on ULXs, presenting different points of view, are those of Fabbiano (2004), Miller and Colbert (2004), Mushotzky (2004), Fabbiano and White (2005) and Fabbiano (2006). Two recent short articles in Nature and Science (McCrady 2004 and Fabbiano 2005) are also useful examples of different perspectives on this subject: McCrady argues for the IMBH interpretation of ULXs. My point of view is that to look for compelling ULX candidates, one must consider only the few sources with luminosities in excess of 1040 erg s-1 that cannot be explained with stellar black hole binaries. The M82 ULX is perhaps the best candidate (e.g., Strohmayer & Mushotzky 2003). The real solution to this problem will require mass measurements from the orbital parameters of a ULX, as it was done for establishing the presence of black holes in some Galactic binaries. This measurement requires high resolution telescopes to identify the companion in crowded stellar fields, and large collecting areas for spectroscopic observations of the companion star.

3. Conclusions

I have discussed recent results on the properties of quiescent SMBHs and on the the possible association of ULXs with IMBHs. Observationally, both topics can now be addressed in X-rays thanks to the sub-acsecond resolution of *Chandra*. Substantial future progress in these X-ray studies will still require high resolution X-ray imaging, but large collecting area will be needed to get more significant spectral results, and to push these observations to higher redshifts. Such capabilities are discussed in the Generation X NASA vision study.

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