The connection between radio-quiet active galactic nuclei and the high/soft state of X-ray binaries

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ABSTRACT
A large sample of active galactic nuclei (AGN) studied here shows a ‘quenching’ of the radio emission that occurs when the luminosity is from a few per cent to about 10 per cent of the Eddington rate, just as is seen in the high/soft state of X-ray binaries. The result holds even when the sample of AGN includes no narrow line Seyfert 1 galaxies (the systems most commonly suggested to be the analogue of the high/soft state). This adds substantially to the body of evidence that AGN show the same spectral state phenomenology and related disc–jet coupling as the stellar mass accreting black holes. That the power-law correlation between X-ray and radio luminosity is the same in both AGN and X-ray binaries and extends below $10^{-7}L_{\text{Edd}}$ strengthens the argument that there is no fundamental difference between the low/hard state and the so-called quiescent state in X-ray binaries. We also discuss possible reasons for the scatter in the radio to X-ray luminosity correlation in the AGN.

Key words: accretion, accretion discs – galaxies: jets – quasars: general – galaxies: Seyfert – X-rays: binaries.

1 INTRODUCTION
Accreting black holes, whether stellar mass binary systems or active galactic nuclei, show many similarities. Both emit radiation over many decades in frequency. Many, but not all, sources in each mass range display evidence for disc accretion in the forms of thermal emission and reflection off the thin disc. Many, but not all, sources in each mass range also have relativistic jets, typically seen through radio observations (see Fender 2003 for a review of the radio properties of X-ray binaries and chapter 2 of Krolik 1999 for a brief introduction to the broad-band properties of active galactic nuclei). Quenching of these radio jets – defined to be a rather sudden drop in the radio emission – has been known about for some time, both in certain classes of active galactic nuclei (AGN; Epstein et al. 1982) and in certain X-ray binaries (Tananbaum et al. 1972; Waltman et al. 1996; Harmon et al. 1997; Fender et al. 1999).

X-ray binaries thought to contain black holes have at least three spectral states. The low/hard state shows X-ray emission well fitted by either a power law with an exponential cut-off at about 200 keV or a thermal Comptonization model with a temperature of about 70 keV, along with a weak or undetected thermal component associated with a geometrically thin accretion disc (Zdziarski 2000, and references within). A so-called ‘quiescent state’ has been suggested to exist in the black hole candidates, but in reality, the X-ray and radio properties of low luminosity black hole candidates form a continuum down to the lowest observable luminosities (Gallo, Fender & Pooley 2003, GFP03). The spectrum of the high/soft state is dominated by thermal component thought to arise in a geometrically thin, optically thick accretion disc (Shakura & Sunyaev 1973; Novikov & Thorne 1973) and also exhibits a weak power law tail without an observable cut-off (e.g. Gierliński et al. 1999). The very high state displays the same two components, but with the steep power law, rather than the thermal component dominating the total flux (see e.g. Miyamoto et al. 1991). Steady radio emission, which can be proved by brightness temperature arguments to come from a region larger than the binary separation of the system, and hence likely from a jet, has been found in the low/hard state, and strong radio flares have been seen during the very high/flaring state (Fender 2003). Neither strong nor steady radio emission has ever been detected in the high/soft state. For a review of spectral states of X-ray binary black holes, see Nowak (1995) and references within.

Models for the hard non-thermal emission generally invoke Comptonization in a low optical depth (i.e. $\tau \lesssim 1$ in the low/hard state and $\tau \lesssim 5$ in the very high state) geometrically thick medium (e.g. Thorne & Price 1975; Shapiro, Lightman & Eardley 1976), although it has also been suggested that the X-ray emission of the low/hard state may be optically thin synchrotron emission from a jet (Markoff, Falcke & Fender 2001, MFF01). None the less, there is general agreement that the high/soft state, the one state thought to be geometrically thin, is the one state where the radio emission is suppressed substantially. Theoretical studies suggest that jet production should be suppressed in thin discs due to the lack of poloidal magnetic fields (Livio, Ogilvie & Pringle 1999; Khanna 1999; Meier, Koide & Uchida 2001).
Radio emission from AGN is also correlated with the X-ray spectral properties of the system, and with the geometry of the inner accretion flow. Radio-loud AGN typically have harder X-ray spectra than radio-quiet AGN (Elvis et al. 1994; Zdziarski et al. 1995). Double-peaked optical emission lines are more often detected in the radio-loud AGN with broad lines than in their radio-quiet, broad-line counterparts (e.g. Eracleous & Halpern 1994); it has been suggested that these lines are reprocessed flux from a large scaleheight X-ray emitting region (e.g. Chen, Halpern & Fillipenko 1989).

More detailed evidence that AGN may follow the same spectral state behavior as the black hole binaries has been scarcer. Analogies have been drawn (i) between the narrow line Seyfert 1 galaxies and the high/soft state (Pounds, Done & Osborne 1995; McHardy et al. 2003), (ii) among low-luminosity AGN, Fanaroff–Riley (FR) I galaxies (i.e. core dominated radio galaxies – see Fanaroff & Riley 1974) and the low/hard state (Meier 2001; Falcke, Körding & Markoff 2003, FKM03) and (iii) between FR II galaxies (i.e. lobe-dominated radio galaxies) and the very high state (Meier 2001). The similarities between the jet ejection events in 3C120 and GRS 1915+105 (Marscher et al. 2002) can be interpreted as evidence for an analogy between the FR II galaxies and the very high state. Finally, GFP03 found that the high luminosity ‘transient’ jets are likely to have higher velocities than the low-luminosity ‘steady’ jets. This is a theoretical prediction of at least one model for explaining the FR I/II dichotomy (Meier 1999), and seems to be supported by the fact that FR I jets tend to be double-sided, while FR II jets tend to be single-sided (e.g. Hardcastle 1995), providing additional evidence in favor of connections between FR I jets and the low/hard state, and between FR II jets and the very high state.

One thing that has not been clear is whether the high/soft state might exist for a broad range of masses of AGN. The narrow line Seyfert 1 galaxies (NLSy1s) which represent the most convincing high/soft state analogues have generally been found to contain black holes at the low-mass end of the AGN mass spectrum (i.e. typically less than about $3 \times 10^6 M_\odot$) and to be accreting at tens of per cent of the Eddington limit. It has been suggested that the radio-quiet quasars may be higher mass examples of the high/soft state (Merloni, Heinz & Di Matteo 2003, MHD03).

If one accepts a few reasonable, albeit unproven, assumptions about the luminosities and mechanisms for state transitions in accreting black hole systems, one can show that a high/soft state might not exist above the mass limits found in the NLSy1s; Meier (2001) suggests that the state transitions for the low/hard state to the high/soft state are caused by transitions from an advection-dominated accretion flow (ADAF; see e.g. Ichimaru 1977; Esin, McClintock & Narayan 1997) to a standard thin disc, while the transitions to the very high state occur when the thin disc becomes radiation pressure dominated. Since the ADAF to thin disc transition should occur at a fraction of the Eddington luminosity independent of mass, while the luminosity in Eddington units where the thin disc becomes radiation-pressure dominated goes as $M^{-1/3}$ (Shakura & Sunyaev 1976), one might expect the thin disc state to disappear when radiation pressure domination sets in below the luminosity for the transition from ADAF to thin disc; a similar, but less detailed argument for the same effect had previously been laid out in Rozanska & Czerny (2000). The soft-to-hard state transitions for black holes in binary systems are generally found to occur at about 2 per cent of the Eddington limit (Maccarone 2003), although the spectral states do show a hysteresis effect (Miyamoto et al. 1995; Smith, Heindl & Swank 2002; Maccarone & Coppi 2003), and the transition from the hard to the soft state can sometimes occur at luminosities about four times as high. The very high state seems to set in at about 20–30 per cent of the Eddington luminosity, and from inspection of the classification table in Miller et al. (2001), one can see that this state can also show hysteresis effects in its transition luminosities and can exist down to about 10 per cent of the Eddington luminosity. Given a factor of 5 ratio for a 10-M$_\odot$ black hole between where the very high state evolves into the high/soft state and where the high/soft state evolves into the low/hard state, one might then expect that no high/soft state systems should exist for black holes more massive than about $4 \times 10^4$ solar masses.

Other models for the state transitions invoking whether the bulk of the power in the accretion flow is dissipated as thermal energy or as magnetic reconnection events can have the same scaling with mass for both the soft/hard and the soft/very high state transitions (Merloni 2003). Searching for the high/soft state analogue in higher mass AGN systems is thus a rather critical step in producing a unified understanding of accretion processes in black hole systems. In this Letter, we will show that AGN accreting in the range of $2–10$ per cent of the Eddington luminosity show a ‘quenching’ in their radio emission similar to that found in Cygnus X-1 and GX 339-4 in their high/soft states (Tananbaum et al. 1972; Fender et al. 1999, GFP), and that more generally, the presence of a hard X-ray spectral component and radio emission are well correlated (e.g. results from GRS 1915+105 in Harmon et al. 1997; Klein-Wolt et al. 2002). This similarity supports the picture where (i) the high/soft state exists for AGN of a rather wide range of masses and (ii) that this high/soft state occurs at the same range of X-ray luminosities as for the Galactic stellar mass black hole candidates.

## 2Data and Analysis

The correlation between radio luminosity and broad-band X-ray luminosity found in GFP03 has been generalized for black holes of all masses to be a $L_R - L_X - M$ correlation, through a multidimensional analysis by MHD03 and through the application of a theoretically predicted mass correction by FKM03. Considerable (i.e. several orders of magnitude) scatter does remain in the AGN sample when this correlation is applied, and the difference cannot be wholly due to measurement errors – additional parameters such as the black hole spin might have a major effect on the radio luminosity.

The exact relation found by MHD03, which we have re-expressed in Eddington units, is:

$$\log \frac{L_R}{L_{\text{edd}}} = 0.60 \log \frac{L_X}{L_{\text{edd}}} + 0.38 \log \frac{M}{M_{\odot}} - 7.33.$$  

(1)

We take the data used here from the compilation of MHD03. The sample includes AGN for which there are good mass, X-ray luminosity and radio luminosity measurements. We exclude the sources in their sample for which there is an upper limit rather than a measurement of one of the three important quantities. We then correct the radio luminosity for the mass term as in equation (1), and plot the corrected radio luminosity in Eddington units versus the broad-band X-ray luminosity in Eddington units in Fig. 1 (a figure similar to fig. 7 of MHD03 and fig. 3b of FKM03).

The X-ray luminosities have been multiplied by a factor of 4.8 as an estimated ‘broad-band’ correction, assuming a $\Gamma = 1.8$ power law spectrum extending from 10 eV to 100 keV, as compared with the 2–10 keV range over which the luminosities have been tabulated. This is not quite a ‘bolometric’ correction – our goal is to make a comparison with the X-ray binaries for which RXTE’s broad-band spectroscopy allows us to observe most of the X-ray emission. We thus do not wish to include the contribution from a component at
High/soft state AGNs

Figure 1. Left-hand panel: the binned corrected AGN, including the narrow line Seyfert 1s. Right-hand panel: the same as the left-hand panel, but with the NLSy1s removed from the sample. The line shows the best fit to the data (with the bins thought to represent the high/soft state excluded from the fit): 

$$\log L_{R, \text{corr}}/L_{\text{EDD}} = (0.64 \pm 0.09)\log L_X/L_{\text{EDD}} - (8.26 \pm 0.40).$$

The different normalization from the MHD03 results comes mostly from the broad-band correction.

wavelengths longward of the peak of the accretion disc, such as the radio jet or a far-infrared bump which may be partly due to AGN-induced star formation or slow reprocessing of AGN photons and may reflect the past, rather than the present luminosity. On the other hand, we do wish to correct for the fact that the thin accretion discs of bright AGN emit primarily in the optical and UV bands, and not in the X-rays. From this point on, when we refer to the ‘broad-band luminosity’, we mean the emission from the disc–corona system, as estimated by the 2–10 keV X-ray luminosity with a correction factor.

Low-luminosity AGNs (i.e., those below about 1 per cent of the Eddington luminosity) tend not have the ‘big blue bump’ associated with the emission from a thin disc, and this broad-band correction factor is well within the range generally accepted (e.g., Ho 1999), although our correction factor is a bit smaller, because we correct only for the high-energy part of the spectrum associated with the disc–corona part of the accretion flow. For the brighter AGN, where the disc emission is stronger (in agreement with the analogy to X-ray binaries), this broad-band correction may be a bit too low, and instead a broad-band correction of a factor of about 15–20 may be more reasonable.

We have also rebinned the available data for the X-ray binaries where simultaneous radio and X-ray points exist and where there are good mass measurements for the systems. The data set is described in GFP03, and references within; we have included data for the following low/hard state sources: GRO J0422+32, XTE J1118+480, 4U 1543–47, XTE J1550–564, Cyg X-1, V404 Cyg & GX 339–4. We have included data from GRS 1915+105 and the transient source sample of Fender & Kuulkers (2001) for the ‘very high state’. The transient source points are not based on strictly simultaneous data, and hence may have some systematic errors introduced, but ignoring these data points does not change the results substantially, because the points lie very close to the data for GRS 1915+105 and because most of the points in the high-luminosity bin come from GRS 1915+105 in any case. As in the AGN case, we have excluded points where the data are upper limits (for fluxes) or lower limits (for masses), and we have applied the mass correction from MHD03 to the data. We have assumed a mass of 6 $M_\odot$ for GX 339–4, the mass function measured by Hynes et al. (2003) and a distance of 4 kpc (Zdziarski et al. 1998), but we note that this is a lower limit on the mass and not an actual measurement. We must include this source despite its not having an actual mass measurement because it is the only X-ray binary with simultaneous radio and X-ray data at the lowest luminosities. We have also tested the correlation assuming a mass of 9 $M_\odot$ and have found that the results are not changed substantially.

In Fig. 2, we have overplotted the binned binary data with the data from the AGN. We have used the same binning ranges for the X-ray...
The high/soft state appears to exist in AGN of all masses in the binary sample as for the AGN sample, but we note that there are no simultaneous radio and X-ray observations of X-ray binaries below about $10^{-6} L_{\text{edd}}$ and very few in the range around $10^{-3} L_{\text{edd}}$. Also, there are relatively few points in our X-ray binary sample very close to 10 per cent of the Eddington luminosity, because the radio data consists primarily of upper limits at this luminosity. We have also refitted the AGN data without including the two ‘quenched’ bins in the correlation, and we find that

$$\log \frac{L_{\text{r,corr}}}{L_{\text{edd}}} = (0.64 \pm 0.09) \log \frac{L_{X}}{L_{\text{edd}}} - (8.26 \pm 0.40);$$

values that correspond much more closely with the X-ray binary correlation found in GFP03. We note here that the low-luminosity AGN and X-ray binaries show a very similar trend, and that the AGN correlation extends several orders of magnitude lower in luminosity than does the X-ray binary correlation. By analogy, this bolsters arguments that suggest that the quiescent state of X-ray binaries is merely an extension of the low/hard state, and that the jet will begin to dominate the total accretion power at very low luminosities (see e.g. Fender, Gallo & Jonker 2003). We also show in Fig. 3 the ratio between the data points and the best fit to the non-quenched data. The AGN points with broad-band luminosity at 3 and 10 per cent of the Eddington luminosity are factors of $\sim 5$ (i.e. 1.7$\sigma$ and 3.5$\sigma$, respectively) below the correlation. We note that due to the application of a broad-band correction factor more appropriate to lower luminosity AGN, the 3 per cent and 10 per cent of Eddington values are likely to be underestimates by a factor of a few, and the points above a few percent of the Eddington limit in the plots should be moved a bit to the right. Sliding the points to the right would push them a bit more below the curve, so the quenching may actually be a bit stronger and more statistically significant the the factor of $\sim 5$ estimate.

3 DISCUSSION

The high/soft state appears to exist in AGN of all masses in the sample which have broad-band luminosities of the order of 5–10 per cent $L_{\text{edd}}$. The effect is not sensitive to whether the systems classified as NLSy1s are included in the sample. The masses of the mean AGN in the bins where the downturn is seen are $5 \times 10^7$ M$_\odot$ and $6 \times 10^7$ M$_\odot$, clearly above the typical masses for the NLSy1s.

The observed correlations also help to underscore the importance of considering the radio-to-X-ray luminosity ratio as a measure of the radio loudness in addition to the more traditional radio-to-optical luminosity ratio. Such an approach does complicate comparisons with some of the historical literature on AGN and optical surveys of AGN do tend to be wider and deeper than those in the X-rays. Still, the optical emission in AGN sometimes is thermal emission from the accretion disc and sometimes is non-thermal emission from a jet; the relative contributions have dependencies on black hole mass, redshift, viewing angle and Eddington fraction. The hard X-rays should always be dominated by emission from the Compton corona (unless one adopts an emission model such as that of MFF01 or Harris & Krawczynski 2002, in which case the hard X-ray emission should often be dominated by the jet). The greater homogeneity of emission mechanisms in the X-rays contrasted with the optical makes correlations discovered in the X-rays easier to interpret. Furthermore, correlations made in the X-ray will be easier to compare with correlations found in the stellar mass black hole candidates.

In hindsight, it is not surprising that the high/soft state exists at roughly the same luminosity for AGN as it does for X-ray binaries. The well-known work of Ledlow & Owen (1996) showed that the FR I radio galaxies lie systematically below the FR II radio galaxies in a plot of radio power versus $R$ magnitude. Using empirical scaling relations between the radio power and bolometric luminosity, and between the $R$ magnitudes and black hole masses, Ghisellini & Celotti (2001) found that the dividing line corresponds to about 2 per cent of the Eddington luminosity. That the scaling relations used by Ghisellini & Celotti (2001) have considerable scatter, while there are very few sources on the ‘wrong’ side of the dividing line between FR I and II galaxies, seemingly may be taken as evidence that there is intrinsically a gap where there are no strong radio galaxies that would have been included in the 3C sample used in the Ledlow & Owen (1996) diagram. The gap, where the high/soft state AGN exist in reality, is then filled in by the low/hard state/FR I systems scattered upwards and very high state/FR II systems scattered downwards. Understanding where the error is in the theoretical predictions (Rozanska & Czerny 2000; Meier 2001) that soft states would not exist for black holes of such mass remains an open question; indeed many other mechanisms for producing state transitions apart from those discussed above also predict a roughly $M^{-1/5}$ dependence of the state transition luminosities (e.g. Merloni 2003). The quenching of the radio jets in the high/soft state range of luminosities seems not to be as extreme for the AGN as it is in the stellar mass systems; the AGN show a drop of a factor of only about 10 in the high/soft state. In the stellar mass black holes, the radio luminosity drops by a factor of at least 30–50 from the extrapolation of the low/hard state correlation (Fender et al. 1999; Corbel et al. 2001). Probably this is partly from contamination of the high/soft state AGN luminosity range due to measurement errors on the masses of the black holes in the AGN and possibly also the hysteresis effects seen in the binary systems. Also, our initial broad-band correction underestimate the real spectral correction factors for sources in this range, leading to an additional underestimate of the quenching effect.

The $L_{X} - L_{R}$ correlation in MHD03 exhibits about three orders of magnitude of scatter. At least one order of magnitude is likely to come from the use of the velocity dispersion–black hole mass technique to measure most of the masses (e.g. Merritt & Ferrarese 2001), but this is unlikely to explain everything. An excellent candidate for the additional scatter would be black hole spin effects, as the black hole spin may affect jet power either directly, if the jet is the result of the extraction of black hole rotational energy (Blandford & Znajek 2001).
1997), or indirectly, if the jet is powered by the rotational energy of the inner disc, which should be larger for a rotating black hole (Blandford & Payne 1982). Given that the high-mass stars, which are the progenitors of stellar mass black holes, have angular momenta much larger than the maximum angular momenta for black holes of the same mass, it would not seem too unreasonable for all stellar mass black holes to be rapidly rotating, as is suggested by some models for the high-frequency quasi-periodic oscillations in the black hole binaries (Rezzolla et al. 2003). On the other hand, black hole–black hole mergers may contribute substantially to the spin evolution of the black holes in AGN and would tend to reduce the spins of most of the black holes produced in the mergers (Merritt 2002; Hughes & Blandford 2003). Hence it would not be too surprising if the black holes in AGN show a much larger range of spins and of jet power at a given mass and luminosity. Testing this hypothesis may be possible through iron line spectroscopy with the planned Constellation-X mission, as iron lines have proved to be a powerful diagnostic of spin in AGN (see e.g. Wilms et al. 2001). It was found in MHD03 that the scatter in the correlation is reduced by eliminating sources in this range; we also find that the eliminating them makes slope of the correlation in the AGN closer to that found in the X-ray binaries.

More broad-band spectroscopy should be undertaken on the putative high/soft state AGN to determine if the systems are truly identical to their lower mass counterparts; the work on NGC 4051 (McHardy et al. 2003) shows that there may be systematic spectral differences between the otherwise rather similar systems, as this system shows similar variability characteristics to the high/soft state of X-ray binaries, and a strong, soft, quasi-thermal component, but shows a substantially harder power-law tail. This should be possible for the brightest sources with a combination of observations from INTEGRAL and from ground-based optical telescopes.

A start on this investigation can be made with the existing data. Numerous studies of large samples of AGN suggest that the typical spectral index $\alpha \approx -0.75$, where $\alpha$ is defined by $F(\nu) \propto \nu^{\alpha}$ (e.g. Wilkes & Elvis 1987; Nandra & Pounds 1994; Lawson & Turner 1997, LT). From examining the individual spectra of the sources in Wilkes & Elvis 1987; Nandra & Pounds 1994; Lawson & Turner 2000; Mkn 761 & PG 1211–Fabian & Piro 2002; PG 0804+349, also shows evidence of rather strong absorption.

One system (PG 1229+204) was rather faint and no spectral fit is available in the literature (see the discussion in LT). Of the nine remaining systems, five clearly show soft excesses (Mkn 279 – see e.g. Weaver, Gelbord & Yaqoob 2001; NGC 7469 – see e.g. DeRosa, Fabian & Piro 2002; PG 0804+761 & PG 1211+143 – see e.g. George et al. 2000; Mkn 335 – see e.g. Turner & Pounds 1988), two show spectra softer than $\alpha = -0.95$ (PG 0052+251 – LT & PG 0953+415 George et al. 2000), one shows a fairly typical X-ray spectrum (PG 1307+085 – LT), and only one shows a spectrum harder than the typical quasar spectrum (PG 1613+658 – LT).

The sources with relatively soft spectra, but no clear soft excess, have higher black hole masses than the sources with clear soft excesses (pushing the peak of their disc component to lower energies as $T_{\text{esc}} \propto M_{\text{BH}}^{-3/4}$), and are at higher redshifts, so the observed soft X-rays probe a slightly higher energy in the rest frame. One thus might expect to need to use the extreme ultraviolet to find their ‘soft X-ray excesses’. It is worth noting that the single truly hard X-ray spectrum belongs to a source which also shows the only flat radio spectrum among the sources (Falcke, Malkan & Biermann 1995; Ho 2002) and has an inferred luminosity just barely higher than 2 per cent of $L_{\text{edd}}$; it may represent a source placed into the wrong bin in the correlation due to measurement errors or hysteresis. Thus, while we have applied ‘mix-and-match’ criteria to discuss the spectra, there seems to be fairly suggestive anecdotal evidence that the spectra of the systems which are well below the GFP03, MHD03 and FKM03 correlation curves and which lie in the 2–10 per cent of $L_{\text{edd}}$ range have systematically softer X-ray spectra than the sources; the correlations between X-ray hardness and radio loudness, found by Elvis et al. (1994) and by Zdziarski et al. (1995) using the classical definition of radio loudness (i.e. the radio-to-optical flux ratio rather than the radio-to-bolometric luminosity ratio), hold up.

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