A link between radio loudness and X-ray/optical properties of AGN

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We have found empirically that the radio loudness of AGN can be understood as function of both the X-ray and optical luminosity. This way of considering the radio loudness was inspired by the hardness-intensity diagrams for X-ray binaries, in which objects follow a definite track with changes to their radio properties occurring in certain regions. We generalize the hardness-intensity diagram to a *disk-fraction luminosity diagram*, which can be used to classify the accretion states both of X-ray binaries and of AGN. Using a sample of nearly 5000 SDSS quasars with ROSAT matches, we show that an AGN is more likely to have a high radio:optical flux ratio when it has a high total luminosity or a large contribution from X-rays. Thus, it is necessary to take into account both the optical and the X-ray properties of quasars in order to understand their radio loudness. The success of categorizing quasars in the same way as X-ray binaries is further evidence for the unification of accretion onto stellar-mass and supermassive compact objects.

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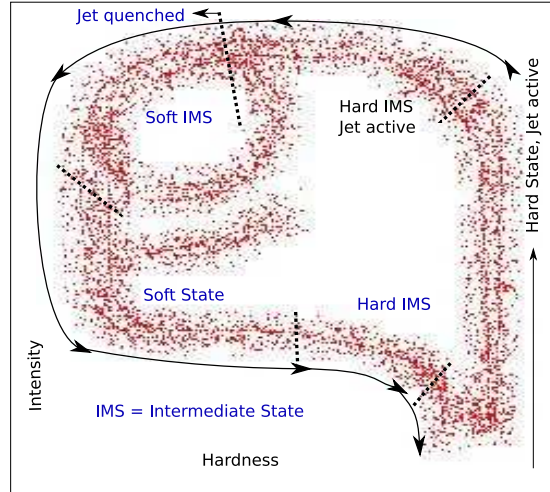
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Figure 1: Sketch of the path traced by X-ray binaries in the hardness-intensity diagram (HID) during an outburst cycle. The sketch shows the correlation between location of the object in the diagram and the jet properties (adapted from Fig. 7 in [4]).

1. Introduction

The discovery of a common scaling relationship between radio luminosity, X-ray luminosity and black-hole mass for Active Galactic Nuclei (AGN) and Black-hole X-ray binaries (BHXRB) binaries [21, 3] is a strong hint that accretion proceeds in a similar way both for stellar-mass and supermassive black holes (see also [22, 11] and the contributions by Körding & Fender and Fender et al. in these proceedings). A number of authors have presented evidence that the accretion states that are observed in BHXRB (see [23] for a review) can also be observed in AGN (for examples, see [14, 21, 3, 7, 10, 5]). Others have searched for further scaling relationships and commonalities between BHXRB and AGN, in particular with respect to timing properties [25, 16], resulting in the recent discovery of a fundamental timing plane shared by BHXRB and AGN [17].

Recently, it has become clear that during an outburst cycle, BHXRBs trace a characteristic path in a plot of X-ray hardness against intensity (hardness-intensity diagram, HID) and that different regions of the HID are associated with different radio properties [4, 2]. Figure 1 gives a sketch of the outburst cycle (sometimes called a "turtlehead diagram" because of its characteristic shape resembling the animal, which has been called mystic [13]): the lowest-luminosity (low/hard) state is associated with a continuous radio jet, which persists as the luminosity increases and the object enters a hard intermediate state (hard IMS). At roughly constant luminosity, the object's spectrum then softens to a soft IMS and radio observations show "rapid ejections" of material, probably indicating a transient but more highly relativistic jet. The spectrum then becomes entirely thermally dominated (soft state) and simultaneously the radio emission is quenched. At lower accretion rates, the spectrum hardens again and the jet radio emission reappears.

It has already been suggested that AGN with different radio properties (radio-"loud" vs. radio-"quiet") correspond to BHXRB with different accretion states [14, 3, 10, 5]. Here, we aim to put this analogy on a firm footing by constructing an equivalent of HIDs that is physically meaningful for both BHXRB and AGN, the disk-fraction luminosity diagram (DFLD). The DFLD plots the

total luminosity (the sum of the thermal contribution from the accretion disc, traced by the optical luminosity, and of non-thermal emission, traced by the X-ray luminosity) against the fractional contribution of non-thermal emission to the total. We find that in the DFLD, AGN segregate by radio loudness, in a manner analogous to that of BHXRBs in HIDs. Thus, we find further evidence for the unification of accretion in BHXRBs and AGN, and provide a framework to understand the physical origin of radio loudness and quietness in AGN, which has been a long-standing puzzle. Full details of this work are published in [12], so this contribution will only highlight the salient features of our approach and findings.

2. Generalizing hardness-intensity to disk-fraction luminosity diagrams (DFLD)

In X-ray binaries, both the thermal emission from the accretion disc and the non-thermal (power-law) X-ray emission (probably arising from the disc's corona) are observed in the X-rays, as soft (peak at photon energies $E_{peak} \leq 2.5\,keV$) and hard ($E_{peak} \geq 50 keV$) X-rays, respectively. The X-ray hardness ratio measures the relative strength of the disc and power-law emission, while the total intensity measures the total accretion rate (although not necessarily in a linear way). Because of the scaling of disc temperature with black hole mass, $T \propto M^{-1/4}$ [24], the disc emission in AGN is now seen in the optical/UV wavelength region, while the power-law emission is still seen in X-rays. Therefore, a pure X-ray hardness ratio misses the disc emission in AGN and does not carry the same information as it does in X-ray binaries.

Therefore, if we want to assess whether AGN behave in the same way as BHXRB in terms of the HID, we need to generalize the HID in a physically meaningful way. As hardness equivalent, we use the *non-thermal fraction* $L_{PL}/(L_D + L_{PL})$, with the useful property of being finite both for 0 and 100% contribution from either component, and set $L_D = L_{Optical}$ and $L_{PL} = L_{X-rays}$ for quasars (see [12] for details on the computation of $L_{Optical}$ and L_{X-rays} from observed fluxes). As intensity equivalent, we use the total luminosity $L_D + L_{PL}$. The advantage of our new definition is that it can be used both for BHXRB and AGN.

3. Constructing a DFLD for a sample of AGN

It was the aim of our work to consider whether AGN show the same separation of accretion state and jet (radio) properties in DFLDs as AGN. In the case of X-ray binaries, individual objects can be followed as they trace out their path in an DFLD during their outburst cycles, which last of order days to months. Since black-hole timescales are expected to scale roughly linearly with mass, this is not possible for AGN (although objects such as 3C 120 [15] might be making small motions in the diagram, such as GRS1915+105 [4]). Hence, we tackle our question in a statistical way, by considering the average radio loudness of AGN as function of their location in the DFLD.

We use two AGN samples, beginning with objects from the 5th data release (DR5) of the Sloan Digital Sky Survey (SDSS [1]) that are identified as quasar by the spectroscopic pipeline, a redshift in the range $0.2 \leq z \leq 2.5$, and that have matches in the ROSAT All-Sky Survey (RASS). Radio fluxes for this sample are obtained from matches in the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey. Both RASS and FIRST matches were taken as provided in the SDSS
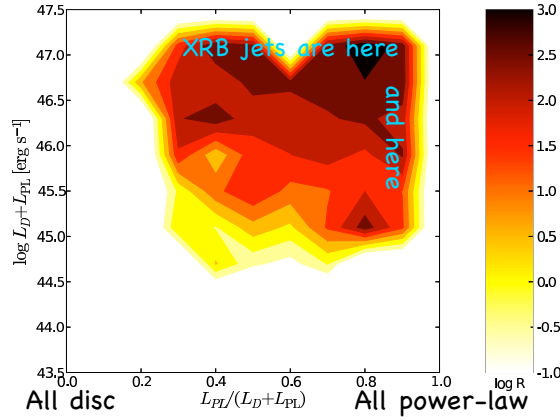
Figure 2: Disc-fraction luminosity diagram (DFLD) showing average radio loudness of 4963 RASS-detected SDSS quasars. The contours give the average radio loudness $R = f(\text{FIRST})/f(B)$ of the quasars in 10×10 bins of total luminosity $L_\text{D} + L_\text{PL}$ and non-thermal fraction $L_\text{PL}/(L_\text{D} + L_\text{PL})$, with contour levels increasing by 0.5 dex. The regions in which X-ray binaries have detectable radio emission from jets are also indicated.
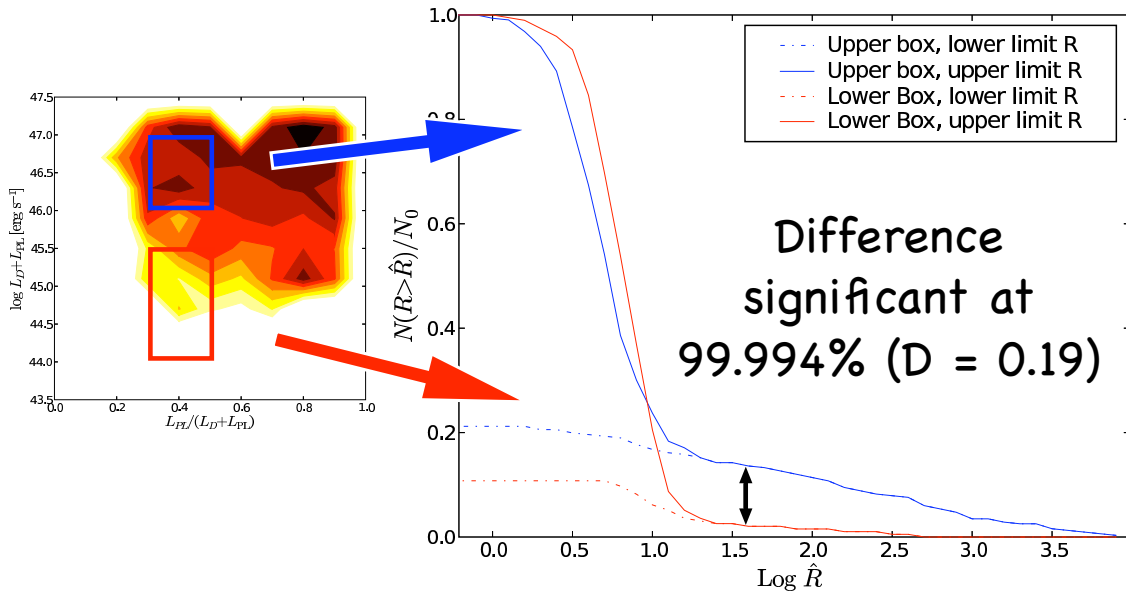

Figure 3: Comparison of the distributions of radio loudness in two areas of the DFLD. A Kolmogorov-Smirnov test shows that there is a high statistical significance of the difference between the two radio loudness distributions. This applies both to the radio loudness R calculated by setting $R = 0$ for sources undetected in FIRST (lower limit R), and for R calculated by setting $R = R_\text{max}$ (upper limit for R from FIRST detection limit).
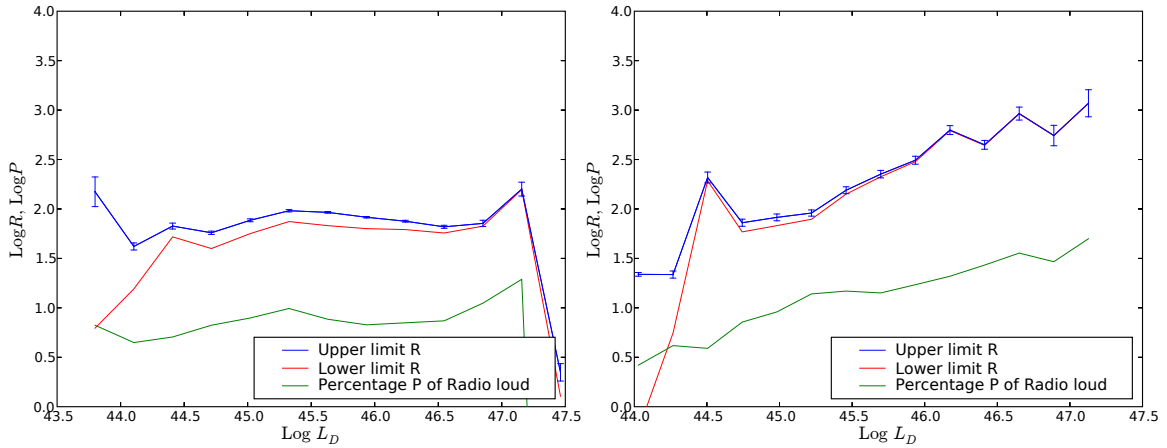
Figure 4: Limits to average radio loudness and percentage of radio-loud sources ($R > 10$) as function of disc luminosity. Left: all 64248 SDSS quasars in the redshift range $0.2 \leq z \leq 2.5$. Right: only the 4963 X-ray detected sources. The error bars give the uncertainty of the mean in each of the bins. R shows a strong correlation with optical luminosity when considering only the RASS-detected sources, but not when considering all quasars independently of their X-ray properties.

Catalog Archive Server database (CAS[1]). There are a total of 64268 objects classified as quasar in the DR5, of which 4963 have a RASS counterpart. Figure 2 shows the average radio loudness of the SDSS quasars in 10×10 bins of non-thermal fraction and total luminosity. Quasars tend to be more radio-loud on average if they have a large total luminosity, and/or a large non-thermal fraction. This difference is quantified by the Kolmogorov-Smirnov test shown in Figure 3. Thus, it is clear that the radio loudness of AGN can only be understood by considering it as a function of *both* the optical and X-ray properties. The relative predominance of non-thermal emission reveals which accretion state the disc is in, and this in turns governs the presence or absence of powerful jets producing strong radio emission.

Figure 4 gives another demonstration of the interdependence of optical, X-ray and radio emission: when considering the average radio loudness R as function of the optical luminosity for all SDSS quasars in our sample, there is no clear correlation with the optical luminosity. However, when the sample is restricted to only the X-ray detected ones, the average R clearly correlates with optical luminosity.

Since the SDSS quasar survey is nearly exclusively sensitive to luminous AGN, we now add a second sample of lower-luminosity AGN. These are taken from [8] with X-ray fluxes taken from the literature or archival data. In the DFLD, the LLAGN lie in the area occupied by XRBs in the low/hard state (perhaps as expected from [6]), which show continuous radio jets (see Figure 5). The LLAGN have much higher average R values than the SDSS quasars, as found by [9].

4. Comparing DFLDs for AGN and XRBs

So far, we have compared the DFLD for AGN and XRBs only qualitatively. We would like to assess more quantitatively whether the population DFLD for AGN, the only one we can construct
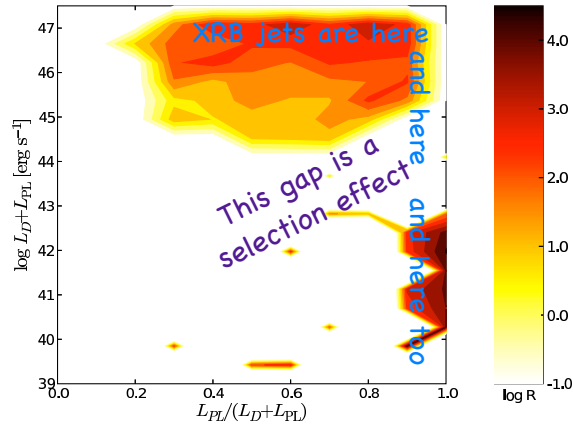
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[1]`http://cas.sdss.org/astrodr5/`

Figure 5: DFLD as in Fig. 2, with the addition of a sample of low-luminosity AGN (LLAGN). The LLAGN lie in the area occupied by XRBs in the low/hard state, which show continuous jets. They are much more radio-loud on average than the SDSS quasars.
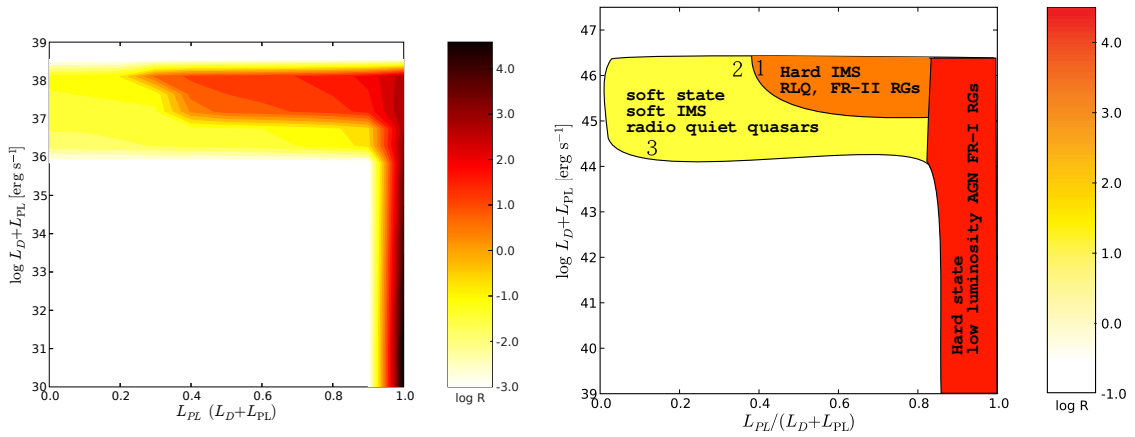

Figure 6: Left: DFLD for a simulated population of XRBs. Right: Unified picture of accretion states in XRBs and AGN.

within human timescales, actually agrees with a population-averaged HID for XRBs. However, the observations (mostly by the *Rossi X-ray Timing Explorer*) that could be used to construct such an observed DFLD for a population of XRBs are not readily accessible to us, and would suffer from uncertainties in the distance, and hence luminosity, determination. Therefore, we have performed a Monte-Carlo simulation of a population of X-ray binaries in outburst cycles. The left panel of Figure 6 shows the resulting averaged DFLD. The strong similarity between the population-averaged DFLD for XRBs and that for our AGN sample strengthens the conclusion that there is a universal accretion mechanism acting in discs both around stellar-mass and around supermassive black holes, with similar disc-jet coupling in both cases. This, like related earlier work [18, 19, 20, 14, 3, 11], suggests the identification of AGN subclasses with XRB states shown in the right-hand panel of Figure 6.

5. Outlook

The presented work is only a first step towards establishing firmly that AGN and XRBs have the same disc-jet coupling. While we considered many possible sources of error and selection effects, it would be highly desirable to repeat our experiment with a sample that has well-measured black-hole masses, and ideally with a volume-limited sample, instead of the approximately flux-limited sample of SDSS quasars used here. In this context, it is a problem that low-luminosity AGN have only been observed in the nearby Universe, where only very few luminous quasars can be found. In XRBs, other observable properties vary with HID position, in addition to the presence or absence of jets: the timing properties [2] and (possibly) the jet Lorentz factor [4]. If the picture presented here is correct, equivalent correlations should be found in AGN (compare [25]). Finally, even radio-"quiet" quasars are not completely radio-silent, implying that the jet is quenched but not turned off completely. The resulting prediction for XRBs is that even objects in the thermally dominated soft state should show low-level radio emission that could be found in very deep radio observations of such objects.

Acknowledgments

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