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The Radio/X-Ray Correlation and the Unification of Low Power Black Holes

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Abstract. We present a unification scheme for active galactic nuclei (AGN) and black hole X-ray binaries (XRBs) using a symbiotic disk/jet model. Scale invariance and energy conservation are used to derive analytical scaling laws for the emission of a jet and allow us to identify the main parameters of the system: the mass of the central black hole and the accretion rate. The developed model can be used to argue for a unifying view of all weakly accreting black holes: a unification of XRBs and AGN. We classify the zoo of AGN in jet and disk dominated sources and test the unification scheme of weakly accreting sources by establishing a universal radio/X-ray correlation for XRBs and AGN. We briefly discuss jets in highly accreting systems.

Key words. X-ray binaries – Active Galactic Nuclei – emission processes

1. Introduction

The relationship of active galactic nuclei (AGN) and black hole X-ray binaries (XRBs) receives much attention in the last years. In particular the multi-band approach to these accreting black holes, e.g., the combination of radio, optical and X-ray observations, leads to new empirical connections (Merloni et al. 2003; Falcke et al. 2004; Abramowicz et al. 2004).

XRBs can mostly be found in two states, namely the low/hard (LH) state (typically found at low accretion rates) and the high/soft (HS) state. The accretion history seems to have an effect when an object changes its state (Maccarone 2003). While the X-ray spectrum of a binary in the LH state is dominated by a hard power law, it is dominated by thermal emission from the accretion disk in the HS state (cf., McClintock 2003). The reason why this strong thermal feature is missing in the LH state is that the inner parts of the accretion disk probably turn into an optically thin radiatively inefficient accretion flow (e.g., an advection dominated accretion flow, Esin et al. 1997). The hard power law can be explained either by Comptonization (see e.g., Shapiro et al. 1976; Haardt & Maraschi 1991), or by synchrotron emission from a relativistic jet (Markoff et al. 2001). In the jet models, the disk is only visible in the spectral range from optical to UV – if at all. If one follows this idea, the spectral energy distribution of an accreting black hole is therefore dominated by jet emission in the LH state and is thermally dominated in the HS state.

AGN on the other hand are found in a huge zoo of different classes (cf., Urry & Padovani 1995). As their central black holes are typi-

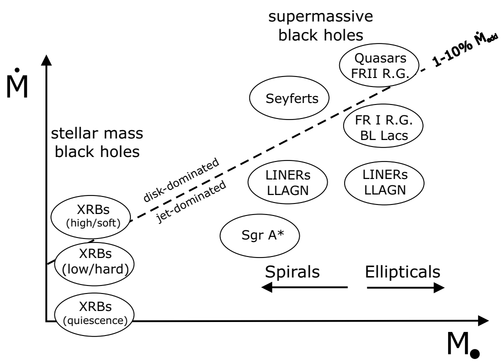

Fig. 1. The unification scheme of Falcke et al. (2004) for accreting black holes in the mass and accretion rate plane. The X-axis denotes the black hole mass and the Y-axis the accretion power. For the AGN zoo we include low luminosity AGN (LLAGN), radio galaxies (RG), low ionization emission region sources (LINER), Seyferts, and quasars.

cally more than 9 orders of magnitude larger, their timescales are similarly larger. Thus, one will not often observe that an AGN changes its state.

Here, we present the main results of Falcke et al. (2004) and briefly compare the radio/X-ray correlation presented here with the one in Merloni et al. (2003). We conclude with a short discussion of jets in highly accreting objects.

2. Low Power Unification: The Radio/X-Ray Correlation

The basic assumption for our unification scheme is that for low power objects the jet emission dominates the SED, i.e., the source is jet-dominated. Furthermore, we assume that the total jet power is coupled with the accretion power (see e.g., Falcke & Biermann 1995). One can calculate the scaling of the jet emission and test it with observations of LH state sources.

The classification into the two states (LH/HS) arises from the XRBs. Due to the large AGN zoo this classification is less obvious for AGN. The strong disk emission in the X-rays seen in HS state XRBs can be observed in the optical for AGN ('the big blue bump') as the accretion disk temperature drops with the central mass. Thus, by searching for thermal emission features from AGN one can also classify the supermassive black holes into the LH and the HS state. The classification suggested by Falcke et al. (2004) is shown in Fig. 1. In addition to the orientation dependent unification schemes for AGN (Urry & Padovani 1995) the main parameters are the accretion rate and the central black hole mass.

This scheme is tested by extending the radio/X-ray correlation found in Galactic XRBs (Corbel et al. 2003; Markoff et al. 2003) to AGN. Using scaling laws for jets where their geometry is scale invariant, (e.g., Falcke & Biermann 1995, Körding 2004) one can show that the X-ray luminosity L_X and the radio luminosity L_R obey:

$$L_X \propto L_R^{1.38} M^{0.81}. \quad (1)$$

This scaling law is only valid in this form if both the radio and X-ray emission are created by synchrotron emission of the jet. For many of the AGN the X-ray emission will not be synchrotron emission but synchrotron-self Compton (SSC) or inverse Compton (IC) emission. However, it is likely that the optical emission from some sources originates from synchrotron emission (see e.g., Chiaberge et al. 1999). To compare the optical fluxes with the X-ray emission found in XRBs, we extrapolate the optical flux to an equivalent X-ray flux using a fixed spectral index. For details see the original paper. A sample of XRBs and AGN is shown in Fig.2 where we used eq. (1) to scale all sources to correspond to a stellar mass black hole. As the analytical calculation suggested the correlation can be extended from XRBs to AGN.

2.1. Comments

Besides the radio/X-ray correlation for XRBs and AGN described here (Falcke et al. 2004) a similar correlation has been published simultaneously by Merloni et al. (2003) (abbreviated by MHM). The main differences arise from the different underlying model used to explain the correlation. Unlike the model described here

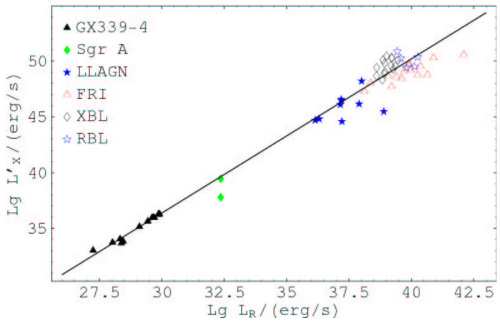

Fig. 2. Radio/equivalent X-ray luminosity correlation for a sample of jet-dominated AGN and XRBs. The X-ray flux has been adjusted to correspond to a black hole mass of $6M_{\odot}$. The term equivalent X-ray flux denotes that this luminosity is extrapolated from the optical fluxes for some AGN sources (FR-I and Bl Lac objects). This extrapolation is motivated by the idea that one has to compare synchrotron emission.

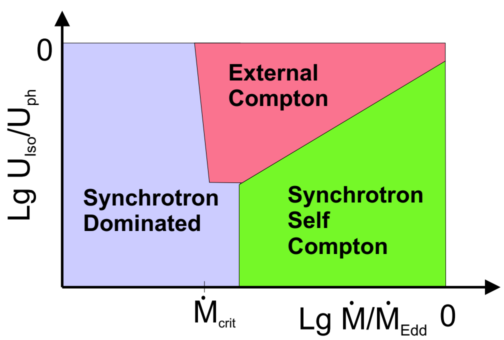

Fig. 3. The dominating emission process of a relativistic jet depending on the accretion rate and the fraction of the isotropic radiation field. The accretion disk is thought to be a radiatively inefficient flow for low accretion rates and an efficient standard disk above the critical accretion rate $\dot{M}_{\rm crit}$.

Merloni et al. (2003) focus on the idea that the X-rays are created by the inefficient accretion flow. This has several implications for the sample selection and the correlation itself:

- The correlation in MHM uses real X-rays while the correlation described here utilizes optical measurements for most AGN and extrapolates them to X-rays. This is done to observe the AGN on the synchrotron peak.
- MHM also include objects in their sample that are classified as high state objects according to our classification based on thermal features. Our sample includes some BL Lac objects corrected for relativistic beaming (errors in the Doppler factor only enter linearly if both X-rays and radio are beamed). These objects are omitted in the MHM sample for the reason that the Doppler-factor is unknown (if the X-ray originate from the accretion flow, the Doppler-factor enters more than quadratically).

3. Higher accretion rates

In the previous sections we have explored the effect of a relativistic jet for low accretion rates. Here, we explore - as a mathematical model - what happens for higher accretion rates, e.g., the direct effect of higher jet power and the illumination from the radiatively efficient accretion flow. XRBs in the HS state do not show a detectable jet in the radio regime. Thus, the jet is either not launched at all or quenched within a couple of gravitational radii before it is detectable in the radio. In AGN also highly accreting objects can show a strong jet. Furthermore, it does not seem to be the case that the jet is quenched for intermediate accretion rates (e.g., the FR I/FR II sources, Ghisellini & Celotti 2001).

Using the idea of scale invariant jets one can establish scaling laws for the jet emission of all important emission processes (e.g., Falcke & Biermann 1995, Körding 2004). The main emission processes are synchrotron emission, SSC and IC emission. All emission processes of the jet have in common that with higher jet powers a relativistic jet gets increasingly efficient in radiating the energy contained in relativistic electrons. Thus, for high power jets cooling will play an important role if the jet is in equipartition. As observations do not show this cooling dominance, the jet will probably be far from equipartion - more energy has to be contained in the magnetic fields than in the observable relativistic particles. This is a further hint that jets have to be launched magnetically.

The scaling laws can also answer the question which emission process dominates the overall emission. The synchrotron emissivity scales quadratically with the accretion rate while the SSC emissivity scales with $\dot{M}^3$. Thus, there has to be an accretion rate at which the SSC emission dominates the synchrotron emission. For a typical parameter-set this happens at a few percent of the Eddington accretion rate.

Besides the potentially higher jet power an other important difference of a jet in the HS state compared with the LH state is the illumination of the jet with photons of the radiatively efficient accretion flow. External Compton cooling will not play an important role, as the disk photons are relativistically deboosted for the jet. However, in case that the disk photons are scattered into an isotropic radiation field, they are boosted and can contribute strongly to the overall emission. The qualitative behavior of the dominating emission process is show in Fig. 3. In they LH state synchrotron emission dominates, only in the HS state external Compton and SSC emission is important. External Compton cooling can - in principle - quench the whole jet as it cools all particles of the jet (synchrotron and SSC only act on the relativistic particles). Thus, if external Compton emission dominates it could lead to an undetectable jet in HS state objects.

4. Conclusions

Weakly accreting XRBs and AGN can be unified using the idea of jet-domination in the LH state. The main parameters – besides the orientation – are the accretion power and the black hole mass.

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