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Unity among Black Holes: Observational Similarities between Galactic Black Holes and Active Galactic Nuclei

Jörn Wilms *

Dr. Karl-Remeis-Sternwarte, Astronomisches Institut der Friedrich-Alexander Universität
Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

Abstract A brief overview of recent observational work on the similarities of Galactic and supermassive black holes is given. It is shown that Galactic black holes and Active Galactic Nuclei both show relativistically broadened iron lines, follow the same relationship between their X-ray and their radio luminosity ($L_{\rm radio} \propto L_{\rm X}^{0.7}$), and show similar X-ray variability. These observations indicate that the accretion flows around black holes scale over many orders of magnitude in mass and luminosity.

Key words: X-rays: binaries — galaxies: active — accretion, accretion physics — black hole physics

1 INTRODUCTION

Observations over the past forty years have proven without doubt that there are at least two kinds of black holes in the universe, which differ by over nine order of magnitude in mass: stellar mass black holes, often also called Galactic black holes, and supermassive black holes, which are thought to exist in the centers of most galaxies. Galactic black holes are thought to be the evolutionary end stages of stars with masses on the zero age main sequence exceeding ∼20 $M_\odot$ (Brown et al. 2001, and references therein). When found in binary systems, they can be among the most luminous X-ray sources in their host galaxies. Supermassive black holes, on the other hand, are thought to be formed early on in the universe and then underwent a phase or rapid growth. Understanding how this growth works in detail is one of the important questions of modern astrophysics, as research in recent years has shown that the growth of supermassive black holes is intimately linked to the history of structure formation in the universe: If material is accreted onto the black hole in the center of a galaxy, an Active Galactic Nucleus (AGN) switches on, which has an energy output comparable to a whole galaxy. This energy release has a profound influence on the surroundings of the AGN, for example by inhibiting star formation (e.g., Rafferty et al. 2006), which in turn evacuates the black hole's fuel source. AGN feedback is therefore thought to be one of the major determinants of galaxy evolution.

Despite the vast differences in luminosity and mass, the accretion processes in galactic black holes and AGN are thought to be very similar. The reason for this belief is that black holes are very simple physical objects, being described solely by their mass, M, their angular momentum, a, and by their charge, q. In an astrophysical context, there is good reason that the material from which the black hole formed was originally electrically neutral, and therefore it is generally assumed that astrophysical black holes are characterized only by M and a. In the simplest model, we would therefore expect that the accretion process onto black holes scales only with M and a as well as the amount of material that is accreted, described through the mass accretion rate $\dot{M}$, and that the same physical processes occur around stellar mass and supermassive black holes. In this picture, we would expect size scales to scale as $r = GM/c^2 \propto M$ (AU for AGN, 10 s of km for galactic black holes) and variability time scales as $\Delta t \propto M$ (tens of ksec for AGN, msec for galactic black holes).

* E-mail: `joern.wilms@sternwarte.uni-erlangen.de`

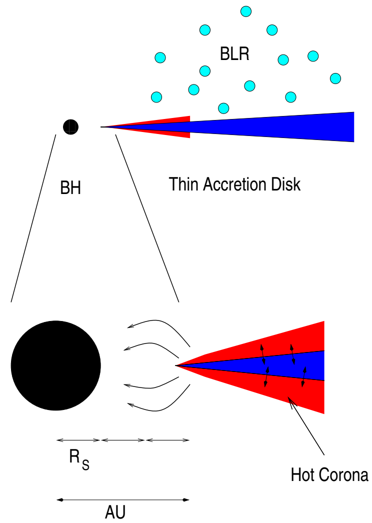

Fig. 1 The different components responsible for the emission from an AGN. See text for a further discussion.

These simple scaling laws mean that in order to understand the physical mechanisms at work around black holes through astronomical observations, observations of stellar mass *and* supermassive black holes are needed: As AGN operate at timescales long compared to human lifetimes, they allow us to perform detailed "snapshot" observations of one state of the accretion process. Observations of stellar mass black holes, on the other hand, will allow us to study the evolution of the accretion flow on timescales that are very long compared to the dynamical timescale of the black hole.

In recent years, multi-wavelength observations of Galactic black holes and of AGN have shown that the picture outlined above is perhaps not too far from the truth: black holes on all mass scales seem to behave similarly, and a number of scaling relationships exist to link stellar mass and supermassive black holes – there is a real unity among black holes. After first briefly summarizing the major components of black hole accretion flow (Sect. 2.1), in the remainder of this review, I will discuss three examples for such similar behavior: the evidence for relativistic effects close to the event horizon through observations of relativistic iron lines (Sect. 2.2), recent evidence for an intimate connection between the properties of the accretion disk and relativistic outflows from the black hole (Sect. 2.3), and finally new results connecting the time variability properties of these systems (Sect. 2.4).

2 UNITY AMONG BLACK HOLES

2.1 Black Hole Accretion Geometry

Over the past decades, observations of accreting black holes in the X-ray and the radio bands have revealed the different components responsible for their emission (Fig. 1). The canonical picture is that in most sources an accretion disk is present in which the accreted material sheds its angular momentum and slowly moves on quasi-circular orbits towards the black hole. The gravitational potential energy released heats the accreted material and is radiated away. For a standard α-accretion disk (Shakura & Sunyaev 1973; Thorne 1974; Riffert & Herold 1995), the radial profile of the disk temperature is $T(r) \propto r^{-3/4}$, and the temperature at the inner edge of the disk scales roughly as $kT_{\rm in} \propto M^{-1/4}$ (Frank, King & Raine 1992). As the disk is optically thick, its local spectrum approximates a black body spectrum, although radiative transport effects in the only partly ionized plasma and Comptonization have a certain effect (e.g., Davis et al. 2005; Shang et al. 2005). The peak emission from the disk comes from close to its inner edge. As a consequence of their different disk temperatures, AGN disks are mainly observed in the ultraviolet, while disks around galactic black holes peak in the X-rays. In the latter objects, the spectra emitted during their higher luminosity "soft states" can be well described by models for the emission of a pure α-type accretion disk, although there is still some discussion about the exact interpretation of the model parameters (Merloni, Fabian & Ross 2000).

In addition to a contribution from the thermal spectrum expected from the accretion disk, the X-ray spectra of lower luminosity AGN such as Seyfert galaxies as well as galactic black holes in their "hard state" are dominated by non-thermal emission. The X-ray spectra of both classes of objects can be well described as power laws with a photon index $\Gamma \sim 1.7$ and an exponential cutoff around 150 keV. As was pointed out, e.g., by Sunyaev & Trümper (1979), such a spectral shape is characteristic of Comptonization, where soft photons from the accretion disk are Compton-upscattered in a hot ($kT_\mathrm{e} \sim 100\,\mathrm{keV}$) electron plasma. To explain the observations, this plasma must be close to the accretion disk, and often a sandwich-like configuration such as that sketched in Figure 1 is envisaged (e.g., Haardt, Maraschi & Ghisellini 1994). Note that Figure 1 is an oversimplification: If the electron plasma really were to cover the disk fully, as shown in the figure, then strong Compton cooling would prevent it from reaching the high temperatures observed (Dove, Wilms & Begelman 1997). For this reason, other possible configurations have been discussed, such as a spherical hot electron cloud which is either completely inside of the inner edge of the accretion disk or has only a slight overlap with it (Dove et al. 1997; Zdziarski et al. 1998).

Finally, most black holes are observed to show some kind of emission at radio bands (Wade & Hjellming 1972; Marscher et al. 2002; Fender, Belloni & Gallo 2004), which is generally attributed to a focused outflow of electrons or a relativistic jet.

To understand black hole accretion, we need to understand how these three components: disk, relativistic plasma, and jet interact. Since the underlying magnetohydrodynamical processes are still outside of the capabilities of todays computers, multiwavelength observations are performed to study this interaction empirically. In the following sections of this review I describe some results from these studies in detail.

2.2 Relativistic Iron Lines

As mentioned in the previous Section, in the region close to the black hole photons from the accretion disk are Compton upscattered in a hot electron plasma. As the disk and the plasma are located close to each other, some of the Compton upscattered photons will be scattered back towards the accretion disk. The physical processes relevant when such hard radiation, with energies up to 150 keV, irradiates the colder accretion disk (where $kT \sim \mathrm{few\ keV}$), can be estimated by noting that the photo-absorption cross section, σ_bf, for a neutral gas of solar composition can be written roughly as

$$\sigma_\mathrm{bf}(E) \approx \sigma_\mathrm{T} \left(\frac{E}{10\,\mathrm{keV}}\right)^{-3}, \tag{1}$$

where σ_T is the Thomson cross section. This behavior of σ_bf then defines the following two regimes:

1. For energies above approximately 10 keV, the photon interacts with the disk material primarily via Compton scattering. Since the relative energy change of the scattered photon in a thermal plasma with temperature T is
$$\frac{\Delta E}{E} \sim \frac{4kT - E}{m_\mathrm{e} c^2}, \tag{2}$$
where the symbols have their usual meaning, the hard photons hitting the disk will mainly be scattered towards lower energies.
2. For photons at energies below approximately 10 keV, photo-absorption in the (partly ionized) gas of the accretion disk is the dominating effect. Softer photons irradiated onto the disk are therefore efficiently absorbed. For material of cosmic abundances, the most important absorption process will be K-shell absorption of iron. Due to the high fluorescence yield of iron, it is very likely that the K-shell vacancy left in an ion after the absorption event will be filled by the transition of an L-shell electron, which results in the emission of a Fe Kα fluorescence photon.

In conclusion, when hard photons irradiate the accretion disk, the resulting "reflection spectrum" can be described by a hump peaking at around 30 keV plus strong fluorescence lines, the most important of which is the Fe Kα line at 6.4–7 keV, depending on the ionization state of the disk (Lightman & White 1988).

In the discussion so far, I described the physical processes occurring in the frame of rest of the reflecting material. As most of the Compton reflection occurs close to the inner edge of the disk, relativistic effects

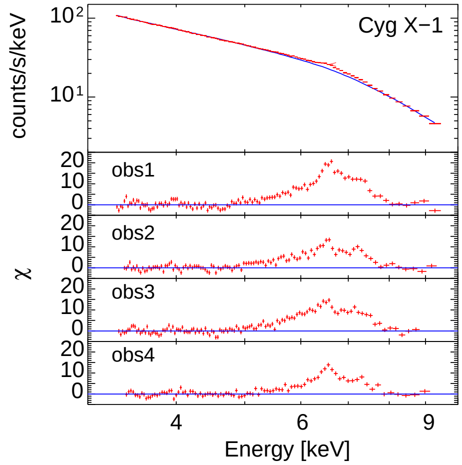

Fig. 2 The shape of the Fe Kα line in four *XMM-Newton* observations of Cygnus X-1 (Fritz et al. 2007).

have to be taken into account. These are large, since the Keplerian speed at the inner edge ($r_{\rm in} = 6GM/c^2$) is approximately

$$v_{\rm in} = \sqrt{\frac{GM}{r}} \sim 0.4c\,. \tag{3}$$

The observed Fe Kα line will therefore be significantly broadened by the (relativistic) Doppler shift. Furthermore, gravitational red-shifting, light bending close to the black hole, and the spin of the black hole also influence the observed line shape. I have summarized the resulting line shapes in the proceedings of a previous Frascati workshop (Wilms, Kendziorra & Reynolds 2006), see Reynolds & Nowak (2003) and Fabian et al. (2000) for more extensive reviews and Dovčiak, Karas & Yaqoob (2004) and Brenneman & Reynolds (2006) for recent calculations.

Relativistic lines were first detected with the Japanese *ASCA* satellite in the Seyfert galaxy MCG−6–30–15 (Tanaka et al. 1995) and confirmed in this object by all subsequent X-ray missions. *XMM-Newton* observations showed the line to be extremely broad when MCG−6–30–15 was in its deep minimum state (Wilms et al. 2001; Fabian & Vaughan 2003), confirming earlier conclusions by Iwasawa et al. (1996) that the black hole in MCG−6–30–15 must be close to maximally rotating. Recent *Suzaku* observations have yielded the best measurement of a relativistic line in an AGN so far and have confirmed the results obtained with the earlier missions (Miniutti et al. 2007). The signal to noise of the newest generation of X-ray satellite measurements is so good that Brenneman & Reynolds (2006) were able to constrain the angular momentum of the black hole in MCG−6–30–15 to $a = 0.989^{+0.009}_{-0.002}$. This measurement is based on *XMM-Newton* data and assumes that no line emission occurs within the innermost stable circular orbit. Similar broad line profiles have now been seen in 10%–20% of all AGN (Guainazzi, Bianchi & Dovčiak 2006; Jiménez-Bailón et al. 2005).

After first discussions of measurements of relativistic lines in galactic black holes (Fabian et al. 1989), measurements with proportional counters such as the Proportional Counter Array on the Rossi X-ray Timing Explorer (*RXTE*), showed first hints at the existence of broad Fe Kα lines in many galactic black holes (e.g., Bałucińska-Church & Church 2000; Nowak, Wilms & Dove 2002). Detailed studies of the line shapes had to wait until the high resolution gratings on *Chandra* became operational (Miller et al. 2002; Miller et al. 2002). These results already showed the lines to be similar to those found in AGN.

In the past two years, improvements in our understanding of the high throughput X-ray sensitive charge coupled devices on *XMM-Newton* has allowed us to measure these profiles with an even higher signal to noise ratio. Figure 2 shows one of the best examples of a relativistic line in a galactic black hole, from *XMM-Newton* observations of Cygnus X-1. Here, the EPIC-pn detector on *XMM-Newton* (Turner et al. 2001) was used in a special mode that allows the detector to transmit all measured events above 2.8 keV

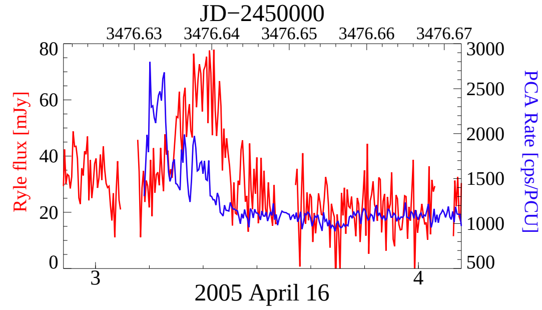

Fig. 3 Simultaneous X-ray and radio observations of Cygnus X-1 on 2005 April 16, showing a bubble ejection event (Wilms et al. 2007).

without telemetry drop outs (Kendziorra et al. 2004). In four simultaneous *XMM-Newton*, *INTEGRAL*, and *RXTE* measurements the line was shown to have the double humped profile characteristic for a relativistic line. Simultaneous broad-band data from *INTEGRAL* and *RXTE* also allow to constrain the strength of the reflection hump, which is consistent with the line measurements (Fritz et al. 2006a,b). The line parameters are consistent with earlier *Chandra* measurements (Miller et al. 2002).

Miller (2007) gives a recent summary of these observations and shows that relativistic lines are seen in virtually all Galactic black holes, typically during state transitions, and that these lines are similar to those found in AGN. Not surprisingly, strong gravity is therefore at work in both kinds of systems.

2.3 The Disk-Jet-Connection

The second unifying theme of stellar mass and supermassive black holes is the presence of jets. While jets had been traditionally associated with extragalactic black holes, the field of study of jets in galactic black holes is much younger, although the presence of radio emission from galactic black holes was known early on (in fact, the association of the X-ray source Cygnus X-1 with its optical companion HDE 226868 was only possible after its position was refined through radio observations; Wade & Hjellming 1972).

With the discovery of microquasars, i.e., black holes showing apparent superluminal motion and therefore having outflows with relativistic speeds, in the past decade it has become apparent that most, if not all, galactic black holes are jet sources (Mirabel & Rodríguez 1999; Fender, Belloni & Gallo 2004, and therein). This discovery is of importance also for extragalactic astronomy, since the shorter dynamical timescales in galactic sources allow us to study the dynamics of jet formation. The observations have shown that there is a very close connection between the presence of a jet and the presence of hard X-ray emission. The most prominent of the observations was the discovery of "bubble ejection" events in microquasars such as GRS 1915+105 (Rodríguez & Mirabel 1995, see Miller-Jones et al. 2005 and Rothstein, Eikenberry & Matthews 2005 for recent results). During these events the hard X-ray emission is found to be strongly variable, and then suddenly drops on a timescale of minutes, before it raises again on a timescales of about 10 minutes. During the drop, the X-ray spectrum hardens and spectral fits of accretion disk spectra show the inner disk radius to recede. After a delay of a few minutes, the source intensity raises in the infrared, followed by a raise in the radio (Rothstein, Eikenberry & Matthews 2005; Mirabel 2004; Eikenberry et al. 1998). A similar event has also been observed in the AGN 3C120, but on timescales that are proportionally longer and therefore required a years long observing campaign (Marscher et al. 2002).

These events are generally interpreted in terms of the "synchrotron bubble model" (van der Laan 1966; Hjellming & Johnston 1988), where the behavior in the X-rays is explained by the emptying out of the inner disk, which results in the ejection of a synchrotron radiation emitting plasma cloud. This cloud adiabatically expands and therefore cools down, such that the peak of the synchrotron spectrum shifts downwards in frequency. While most prominently observed in microquasars, with the observation of a simultaneous radio–X-ray flare in Cygnus X-1 (Fig. 3), it was found that bubble ejection events are also seen in "normal" black holes, in which no superluminal motion has yet been detected (Wilms et al. 2007).

Observations of such bubble ejection events show that there is a tight connection between the X-ray and the radio emission. Furthermore, at least in some sources the overall power of the jet is also comparable

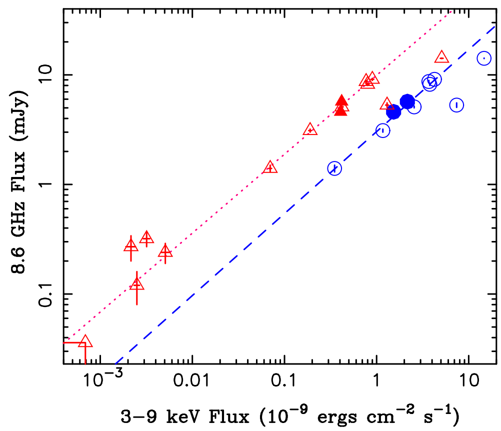

Fig. 4 Radio versus X-ray flux for two outbursts of GX 339−4 (after Nowak et al. 2005, fig. 5). While Eq. (4) holds for both outbursts, the normalization constant changes, indicating that something else than the black hole mass influences the efficiency of the radiative processes in this system.

to the X-ray luminosity, indicating that a significant fraction of the accreted power is ejected in the radio outflow (Gallo et al. 2005; Maccarone & Koerding 2006). Furthermore, as nicely illustrated in observations of the black hole candidate GX 339−4 (Belloni et al. 2006) and in the long-term radio and X-ray lightcurves of Cyg X-1 (Wilms et al. 2006), the radio and the X-ray behavior are generally also correlated on longer timescales. Quantifying this correlation in observations of an X-ray outburst of GX 339−4, Corbel et al. (2003) found that

$$F_{\mathrm{radio}} \propto F_{\mathrm{X,3-20\,keV}}^{0.71}, \tag{4}$$

(see also Hannikainen et al. 1998 and Markoff et al. 2003). This relationship was later extended by Gallo, Fender & Pooley (2003), who showed that Equation (4) also holds for a selected sample of black hole candidates, although some intrinsic scatter was present. For example, at first glance Cyg X-1 did not seem to fit the correlations at all. As shown by Nowak et al. (2005), however, when using the 20–100 keV X-ray flux instead of the soft X-ray flux, a similar correlation also holds for Cyg X-1. This result is taken to mean that the medium responsible for the hard spectral component is related to the radio emission, and that the soft spectral band can be “contaminated” by other emission.

Equation 4 was first obtained by empirical means, i.e., by looking at observational data. As was pointed out by Heinz & Sunyaev (2003), for scale-invariant jets the jet properties depend only on M_{BH}, $\dot{M}$, and the black hole’s spin. The scatter in the L_{radio}-L_{X}-relationship was therefore posited to be due to the black hole mass. Ignoring the spin for a moment, this means that there is a “fundamental plane relationship”, which provides a relationship between L_{X}, L_{radio}, and M_{BH}. As was shown by Merloni, Heinz & di Matteo (2003) and, independently, by Falcke, Körding & Markoff (2004), when taking the mass of the black hole into account, then Equation (4) can be extended to include AGN – showing again that there is “unity among black holes”. Merloni, Heinz & di Matteo (2003) find that for Galactic black holes and for AGN,

$$\log L_{\mathrm{radio}} = (0.60 \pm 0.11) \log L_{\mathrm{X}} + (0.78^{+0.11}_{-0.09}) \log M_{\mathrm{BH}} + 7.33^{+4.05}_{-4.07}. \tag{5}$$

This relationship holds over 15 orders of magnitude in L_{X} and L_{radio}, and ~10 orders of magnitude in M_{BH}.

As for all fundamental relationships in physics, there is some danger that Equation (5) might be due to a selection effect. Merloni et al. (2006) present an exhaustive discussion of possible biases influencing the relation, showing that on the basis of the available data, the correlation appears to be real. It should be noted, however, that there is observational evidence that despite these statistical tests the fundamental plane relationship alone cannot explain the relationships between the radio and the X-ray fluxes. The reason is depicted in Figure 4, which shows the radio and X-ray fluxes for two different outbursts of GX 339−4

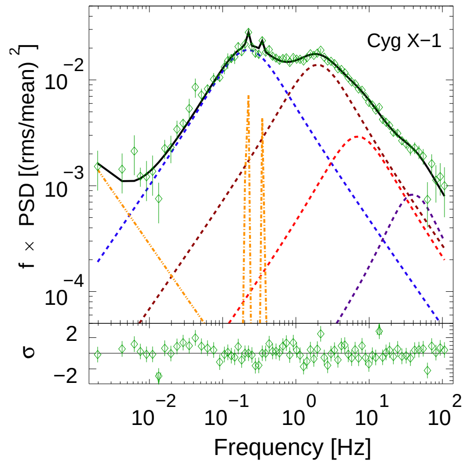

Fig. 5 Example for a power spectrum of Cyg X-1 (after Pottschmidt et al. 2003). The power spectrum can be well described as the sum of several Lorentzians. To show these components more clearly, the power spectrum has been multiplied by the frequency.

(Nowak et al. 2005). While the fluxes from both outbursts follow approximately a $F_{\rm radio} \propto F_{\rm X}^{0.71}$ relationship, the normalization of the correlation is clearly different. As it is very unlikely that the black hole mass has changed between these two outbursts, these observations indicate that some other, hitherto unknown, physical parameter is also influencing the efficiency of the radio and/or jet emission. In addition to these observations in one object, I also note that there are four more hard state black holes that are also underluminous in the radio with respect to the correlation (Gallo 2007, see also Xue & Cui 2007).

Despite all of these caveats, however, Equation (5) is a remarkable relation between two observables, $L_{\rm radio}$ and $L_{\rm X}$, and the black hole mass, and illustrates again that black holes appear to be more or less scale invariant over many orders of magnitude in luminosity and mass. The relationship therefore deserves further study.

2.4 Black Hole Timing

The last subject of this contribution on similarities between Galactic black holes and supermassive black holes is that of X-ray timing. This subject has been strongly advanced over the past decade, thanks to the long monitoring campaigns that have become possible due to the scheduling flexibility of *RXTE*.

Since *EXOSAT*, it has been known that the power spectrum of Galactic black holes can be well described by a broken power law, with the break frequency depending on the state of the source (Belloni & Hasinger 1990): Once the spectral shape of the source becomes softer, its variability decreases and the break moves to a higher frequency. In recent years, as illustrated in Figure 5, it has been realized that this broken power law shape can be well described by the sum of several broad Lorentzians (Nowak 2000; Pottschmidt et al. 2003). In this picture, the Belloni & Hasinger (1990)-effect is due to a dependency of the characteristic frequencies of these Lorentzians with spectral shape. As an aside, we note that the Lorentzians are also seen at higher energies, above 10 keV (Pottschmidt et al. 2006) and that the relations between these frequencies obey the same correlations that have been described, e.g., by Belloni, Psaltis & van der Klis (2002) for the characteristic frequencies found in neutron star X-ray binaries.

The *RXTE* monitoring of AGN has allowed to show, for the first time, that the power spectra of AGN are very similar to those of Galactic black holes (Edelson & Nandra 1999; McHardy et al. 2004, 2005, and therein). This similarity extends to recent successes in describing AGN power spectra with Lorentzians (Pessah 2007). Note that it is puzzling that in general the power spectra of Seyfert galaxies seem to be closer related to those of Galactic black holes in the soft state (McHardy et al. 2004), although the energy spectra resemble the hard spectra.

According to a model first suggested by Miyamoto & Kitamoto (1989) and later expanded upon, e.g., by Psaltis & Norman (2001), Nowak et al. (1999), or Churazov, Gilfanov & Revnivtsev (2001), the origin of the Lorentzians is often taken to be related to damped oscillations in the accretion disk. Here, a white noise source sits at outer radii of the accretion disk. Disturbances propagate inwards, exciting damped oscillations in the disk. The characteristic frequencies of the Lorentzians are therefore assumed to be related to characteristic disk oscillations, which in turn can be assumed to scale with the Kepler frequency. It is therefore natural to posit that characteristic timescales in the X-ray spectrum scale with the mass of the black hole. As the disk changes with $\dot{M}$, in addition it seems likely that the frequencies are related to $\dot{M}$, and therefore the bolometric luminosity, $L_{\rm bol}$. Noting this relation between the black hole mass, the luminosity, and the characteristic timescale, in a recent important paper, McHardy et al. (2006) show that such a simple relation can indeed be found in the data. From selected data from AGN and Galactic black holes in their soft state, McHardy et al. (2006) find

$$\log T_{\rm break} = (2.10 \pm 0.15) \log M_{\rm BH} - (0.98 \pm 0.15) \log L_{\rm bol} - (2.32 \pm 0.20). \quad (6)$$

Since $L_{\rm bol} \sim \dot{m}_{\rm Edd} \dot{L}_{\rm Edd}$, where $\dot{m}_{\rm Edd} = \dot{M}/\dot{M}_{\rm Edd}$, this relation corresponds to

$$T_{\rm break} \propto M_{\rm BH}^{1.12} \dot{m}_{\rm Edd}^{-0.98}. \quad (7)$$

Note that it is possible to extend this relation to hard state sources if one allows for a constant offset in the characteristic frequencies between the soft state and the hard state (Körding et al. 2007). Such an offset is not too improbable: as outlined in the previous sections, the accretion geometries in the different states are rather different, in that the soft state lacks a (strong) jet and/or the Comptonizing plasma. Therefore one would expect the damping properties of the disk to be different in these two states.

In conclusion, the timing properties of AGN and Galactic black holes also obey the same scaling relationships, and the two types of sources are similar in their variability.

3 SUMMARY

In this review I have summarized recent observational work on the similarities between stellar mass black holes and supermassive black holes in Active Galactic Nuclei. These similarities were

1. the presence of relativistically broadened iron fluorescence lines,
2. the recent results on correlations between the X-ray and the radio emission from black holes, pointing at the importance of radio emitting outflows from these systems for their overall energetics, and
3. the remarkable similarities in the X-ray variability of AGN and Galactic black holes.

Despite the problems with the physical interpretation of these results, it is encouraging that the "unity among black holes" that was postulated in the past decades now seems to be more and more corroborated by observational date. It is to be hoped that the instrumentation planned for the next decade will allow us to study these relationships between black holes of different sizes in even more detail allowing the development of a consistent unifying picture of black hole accretion.

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DISCUSSION

JIM BEALL: In the model usually considered, the radio blobs emit their radiation by van der Laan expansion. Can you comment on the relationship between the radio and X-rays in various scenarios?

JÖRN WILMS: There is general agreement that the observed radio emission is due to synchrotron radiation. In the X-rays, this picture is less clear. As has been shown by Sera Markoff and collaborators (Markoff & Nowak 2004; Markoff, Nowak & Wilms 2005), it is possible to describe the broad band spectrum of Galactic black holes using jet models. Here, the X-rays originate in the base of the jet and are mainly due to synchrotron self-Compton radiation. If this picture is true, then the radio–X-ray-lightcurves are rather simply explained with the van der Laan (1966) model. It should be noted, however, that the jet-model is not yet generally accepted (Ibragimov, Zdziarski & Poutanen 2007). If one posits the X-rays to be due to Comptonization, then the explanation of the radio–X-ray flares would be more complicated, e.g., invoking changes in the Compton corona on short timescales, e.g., due to short timescale variations of $\dot{M}$. I am not aware of any modeling performed for flares in this picture.

SYLVAIN CHATY: Do you have any idea, why Cygnus X-1, GX 339−4, and XTE J1650−500 do not follow the radio–X-ray correlation?

JÖRN WILMS: First of all it should be stressed that some of these sources, and Cyg X-1 for sure, clearly do not follow the $L_{\rm radio} \propto L_{\rm X}^{0.7}$ correlation when the X-ray luminosity is measured below 10 keV or so. I believe that this is due to the fact that the radio–X-ray correlation is in reality a correlation between the radio emission and the luminosity in the hard (power-law) component of the X-ray emission. What is often done is to measure $L_{\rm X}$ from the *RXTE*-ASM count rates. The ASM, however, does not allow one to do the spectroscopic studies to disentangle the soft and hard components, and pointed observations are required. I believe that at least for some of these sources, a more detailed study from pointed observations will reveal that these sources follow the correlations. However, as illustrated for GX 339−4, even when using a proper analysis based on pointed observations, the normalization of the relation changes. The origin for this change is not yet known.