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The relation between radio and X-ray luminosity of black hole binaries: affected by inner cool disks?

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ABSTRACT

Context. Observations of the black hole X-ray binaries GX 339-4 and V404 Cygni have brought evidence of a strong correlation between radio and X-ray emission during the hard spectral state; however, now more and more sources, the so-called "outliers", are found with a radio emission noticeably below the established "standard" relation. Several explanations have already been considered, but the existence of dual tracks is not yet fully understood.

Aims. We suggest that in the hard spectral state re-condensation of gas from the corona into a cool, weak inner disk can provide additional soft photons for Comptonization, leading to a higher X-ray luminosity in combination with rather unchanged radio emission, which presumably traces the mass accretion rate.

Methods. As an example, we determined how much additional luminosity due to photons from an underlying disk would be needed to explain the data from the representative outlier source H1743-322.

Results. From the comparison with calculations of Compton spectra with and without the photons from an underlying disk, we find that the required additional X-ray luminosity lies well in the range obtained from theoretical models of the accretion flow.

Conclusions. The radio/X-ray luminosity relation resulting from Comptonization of additional photons from a weak, cool inner disk during the hard spectral state can explain the observations of the outlier sources, especially the data for H1743-322, the source with the most detailed observations. The existence or non-existence of weak inner disks on the two tracks might point to a difference in the magnetic fields of the companion stars. These could affect the effective viscosity and the thermal conductivity, hence also the re-condensation process.

Key words. accretion, accretion disks – black hole physics – X-rays: individuals: GX 339-4 – X-rays: individuals: V404 Cyg – X-rays: individuals: H1743-322 – X-rays: binaries

1. Introduction

Stellar-mass black hole binaries are sources where gas is accreted from a companion star either from a massive star, in high-mass X-ray binaries, or from a star of a few solar masses in low-mass X-ray binaries (LMXB). The LMXBs are typically transient systems, which are often detected during an outburst and observed mainly during outbursts, but these binaries have long time intervals of low luminosity between the bright states. Matter flows continuously from the companion star towards the black hole via an accretion disk. During phases of low luminosity, the accretion disk can be truncated, and in the inner regions surrounding the central star, the disk is replaced by an advection-dominated radiatively inefficient flow, ADAF (Narayan & Yi 1994).

The generally accepted mechanism that drives the outburst cycles is the ionization instability in the disk, which was developed earlier in the model for dwarf nova outbursts (Meyer & Meyer-Hofmeister 1981). But in X-ray binaries, the outburst features are more complex owing to the irradiation of the disk by the innermost hot regions. The enormous variety in the outburst behaviour of X-ray binaries was already pointed out by Chen et al. (1997). In their recent review McClintock & Remillard (2006) focus on the 18 black holes with measured masses. The behaviour and the properties of binaries with dynamically confirmed black holes have been reviewed by Remillard & McClintock (2006).

The possible schemes of accretion geometry lead to quite different spectra. If the accretion disk reaches inward towards the last stable orbit, the spectrum is dominated by a strong thermal component, the state is known as the high/soft state. The second main spectral state, the low/hard state, is characterized by a power-law continuum with a spectral index $\Gamma \leq 1.8$ (Remillard & McClintock 2006). Besides these two main states, an intermediate state and a state of very high accretion rate are known. Done et al. (2007) have investigated how a coherent picture of the physics of the accretion flow onto black holes can be developed from the increasing number of observations. Dunn et al. (2010) report on a consistent and comprehensive spectral analysis of X-ray binaries. Gilfanov (2010) have reviewed the current status of the theoretical understanding of accretion and formation of the X-ray radiation. Investigations of observed spectra of several selected black hole binaries have been carried out to study the emission of LMXBs.

New insight comes with the results of the recent *Swift* survey of all known stellar-mass black hole binaries (Reynolds & Miller 2013). In comparison to RXTE, the low-energy X-ray cutoff allows studying the disks at lower energies, whereas previously a cool inner disk would have been outside the RXTE low-energy cutoff at 3 keV. This is important for analyzing inner regions, and it can affect the relation between radio and X-ray luminosity investigated here. The ejection of relativistic jets occurs at the transition from the hard spectral state to the intermediate state during the rise of the outburst (see the "jet

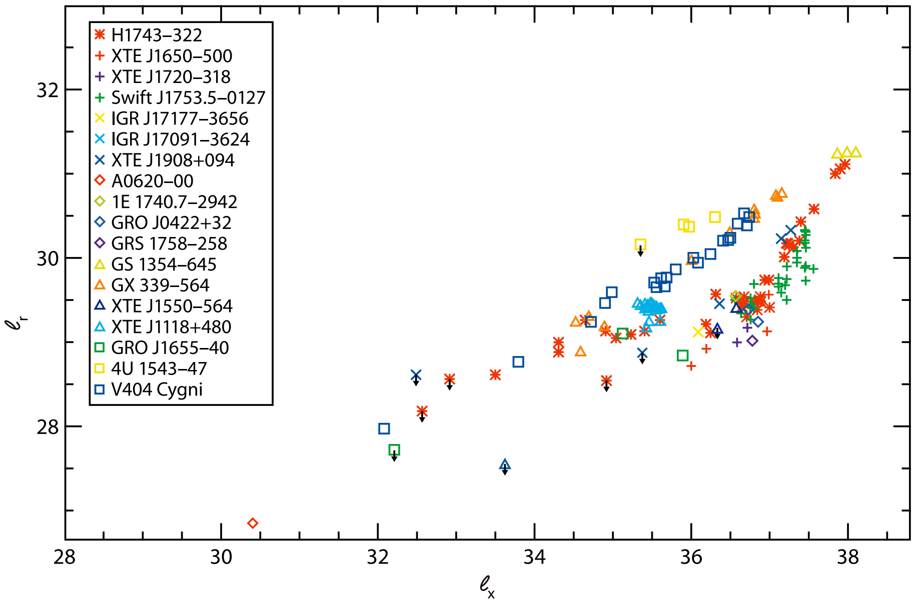

Fig. 1. Observed radio and X-ray luminosities of 18 X-ray binaries, adopted from Gallo, Miller, and Fender (2012, Fig. 1; the original drawing also shows data for Cyg X-1, GRS 1915+105 and radio upper limits of quiescent BHXBs from Miller-Jones et al. (2011). Distances of all sources are listed and uncertain distances are indicated.)

line" in the LMXBs hardness-intensity diagram of Fender et al. 2004). The radio emission from a different type of jet, a so-called compact jet, occurs in the hard spectral state, extending to very low luminosities (for a recent review of radio emission and jets see Gallo 2010). The radio emission in the hard state is usually characterized by a flat or slightly inverted spectrum, interpreted as self-absorbed synchrotron emission from a steady, collimated compact jet. Observations have provided evidence that a strong connection exists between radio and X-ray emission during the hard state: an universal correlation of the form $L_{\rm radio} \propto L_{\rm X}^{0.7}$ was found by Gallo, Fender & Pooley (2003), dominated by the observations of GX 339-4 and V404 Cyg.

For GX 339-4 a large sample of quasi-simultaneous radio and X-ray observations were collected during the many outbursts from 1997 to 2011 (Corbel et al. 2013). V404 Cyg was observed during the decay of the 1989 outburst (Han & Hjellming 1992; Kitamoto et al. 1990). A definitive correlation study is presented by Corbel et al. (2008), resulting in a slight change of the correlation index. The correlation appears to be maintained down to the quiescent level of at least two sources, V404 Cyg, A 0620-00, and possibly also GX 339-4 (Corbel et al. 2003; Gallo et al. 2003, 2006). Important for understanding the accretion geometry in supermassive black holes, the correlation found for LMXBs, was extended to active galactic nuclei (AGN) to provide a universal scaling law, which is the definition of the "fundamental plane" of black hole activity (Merloni et al. 2003; Falcke et al. 2004). It is therefore interesting, also in this connection, that recent observations of a number of sources now seem to indicate that the established correlation is not universal.

During recent years, quite an effort has been made to get quasi-simultaneous X-ray and radio observations, leading to the result that for several sources, such as XTE J1550-564, XTE 1650-500, GRO J1655-40, Swift J1753.5-0127, and H1743-322, for a given X-ray luminosity, the simultaneous radio luminosity is lower than that of the standard correlation. These sources were classified as outliers. (Further information can be found for the sources XTE J1550-564 and GRO J1655-40 in the work by Calvelo et al. 2010, for XTE J1650-500 in work by Corbel et al. 2004, for Swift J1753.5-012 and H1743-322 in the papers by Soleri et al. 2010 and Coriat et al. 2011.) In the following we refer to the standard track and the outliers as upper and lower track, respectively. Gallo, Miller & Fender (2012), presented a data set of more than hundred simultaneous X-ray and radio observations of 18 different black hole X-ray binaries in hard state.

Since this largest data set clearly documents the many sources at the lower track, we show their data set in our Fig. 1. We note a remarkable feature: at some lower value of radio luminosity, the lower track seems to end, and instead a transition towards the upper track is indicated. At the upper end of the considered range, the X-ray luminosity is a few percent of the Eddington luminosity. Above this luminosity the transition to the high/soft state occurs, and the compact jet is quenched. Coriat et al. (2011) argue that the steep high-luminosity part of the lower track can be explained by a radiatively efficient flow. Employing clustering techniques, Gallo et al. (2012) came to the conclusion that the observational data of the two tracks, the upper and the lower ones, are clearly distinct and that there is "no compelling explanation for this behaviour".

We here present a new suggestion. While mostly one searches for an explanation for why for the same X-ray luminosity the radio luminosity is lower on the lower track, we turn the question around and ask why for the same radio luminosity the X-ray luminosity is higher on the lower track than on the upper track. We are motivated here by the perception that the jet energy and the corresponding radio luminosity originate in the dominant hard state ADAF-corona, from which the X-ray luminosity takes away only a smaller fraction. We propose that the increased X-ray luminosity can be due to additional soft photons from a weak inner disk. Such an inner disk is sustained by re-condensation of matter from the corona into the disk, for accretion rates greater than about $10^{-4}\ \dot{M}_{\rm Edd}$ (Meyer et al. 2007; Liu et al. 2007). That the re-condensation does not work at low accretion rates is important for our suggestion since this could naturally explain that the lower track ends at a certain luminosity that is related to the quiescent state.

In Sect. 2 we summarize the simultaneous radio and X-ray observations during hard state, as well as the previously made suggestions to explain this feature. In Sects. 3 and 4 we refer to earlier work about the existence of an inner disk during the hard state, and we discuss how much additional luminosity could arise from this thermal component to affect the radio/X-ray correlation. We compare our results for a higher X-ray luminosity due to additional photons from an inner weak disk with the observations for H1743-322 in Sect. 5. In Sect. 6 we especially discuss what causes the difference to the sources on the upper track, which could imply that in the systems at the standard track with the correlation $L_{\rm radio} \propto L_{\rm X}^{0.7}$ (or with an exponent 0.6), no inner disks are present.

2. Observations and previous suggestions

As mentioned above, the most complete compilation of simultaneous radio and X-ray observations is by Gallo et al. (2012). The full data set includes 165 hard-state observations of 18 different X-ray binaries (Fig. 1). Some distance measurements are uncertain (pointed out in the original figure), but this cannot explain the two-track feature. Remarkable is that by excluding the few observations during quiescence within the range of X-ray luminosities where the two tracks exist, the values of a chosen source definitely lie on either one or the other side of the tracks. Ratti et al. (2012) found the radio luminosity for an additional source XTE J1752-223, on the lower track. A second recent source, MAXI J1659-152 (Jonker et al. 2012; van der Horst 2013), also was found close to the lower track.

Already in 2003 the tight correlation between radio and X-ray flux was found for GX 339-4 (Corbel et al. 2003) and for V404 Cyg (Gallo et al. 2003). While for the latter source all information comes from one outburst (decline) in 1989, for GX 339-4 a large sample of data includes observations over a 15 year period (Corbel et al. 2013). All these radio and X-ray luminosities lie on the standard correlation. The lower track is populated by data from a large number of X-ray binaries (see Fig. 1). The source XTE J1118+480 is sometimes listed under the outliers, but the luminosity values are relatively high.

Coriat et al. 2011 present the most detailed information with simultaneous radio and X-ray observations for seven outbursts of H1743-322 between 2003 and 2010. In their paper the observed radio and X-ray flux densities are listed for all observations and the position of the particular observation in the respective hardness-intensity diagram of that outburst is shown. We discuss these values in our comparison of theoretical results and observations in Sect. 4. – Several recent investigations have focused on the question of what might cause the two different relations between radio and X-ray luminosity. Gallo et al. (2012) summarize these suggestions. The effects discussed are hysteresis behaviour (Russell et al. 2007), a large scatter due to differences in the strength of the magnetic field from source to source (Casella & Pe'er 2009; Pe'er & Casella 2009), different slopes of the tracks, which otherwise are not expected within the jet-accretion models (Markoff et al. 2001, 2003), or the low and high spin of the black hole (Fender et al. 2010). Coriat et al. (2011) suggest that the steep part of the lower track can be understood in the framework of radiatively efficient accretion, and the outflow properties of the jet were also considered as a possible cause for the two tracks. Soleri & Fender (2011) discuss whether the parameters of the binary systems (orbital period, disk size, inclination), as well as the outburst properties (e.g. low/hard state only outbursts), show any correlation with the energy output of the jet, but did not find an obvious dependence.

3. The existence of cool inner disks during the hard state

The configuration of the accretion flow towards a black hole, which depends on the accretion rate, as displayed by Esin et al. (1997), is commonly accepted. (The observed hysteresis in the spectral state transition can be understood as an irradiation effect of the hard state accretion, Meyer-Hofmeister et al. 2005.) Still under debate is the disk truncation. A new discussion arose a few years ago, initiated by new observations that indicate a weak soft thermal component in the spectra of GX 339-4 (Miller et al. 2006a) and Swift J1753.5-127 (Miller et al. 2006b), for example. Weak thermal components had already been marginally found for some sources earlier, always at a time close to an intermediate spectral state. It is clear that in outburst decline, at the time when the spectral transition happens, the accretion geometry might be complex. The change from disk accretion to accretion via a hot flow occurs when the mass flow in the disk becomes low, lower than the evaporation rate, so that all matter in the disk is evaporated and flows farther inward as coronal hot gas (Meyer et al. 2000a,b). This might first happen at that distance from the black hole where evaporation is most efficient, e.g. at a hundred or more Schwarzschild radii, depending on such parameters as viscosity and the ratio of magnetic pressure to total pressure (Qian et al. 2007). With more decreasing mass flow, the percentage of coronal flow compared to the total flow increases, and less gas is accreted via the inner part of the still co-existing disk. The remaining inner disk would rapidly disappear, if not sustained by re-condensation of gas from the corona into the disk (Meyer et al. 2007; Liu et al. 2007). The re-condensation of gas from the ADAF into the inner disk follows from thermal conduction between disk and hot flow.

Such an innermost disk is an essential feature of the accretion geometry during the change from the soft to the hard spectral state. The innermost disk is weak and thus clearly distinguishable from a standard disk in soft state. Its appearance is not in conflict with the basic picture of disk truncation as sometimes surmised.

An underlying disk provides soft photons for the Comptonization by electrons in the hot advection-dominated flow. The emission from the inner cool disk is partly at very low energies, below 0.1 keV, therefore not detectable with RXTE with the low-energy cutoff at ~3 keV. In the past, observational data were classified as during spectral hard state if no accretion disk component was needed to correctly fit the data above 3 keV, besides a power-law photon index $\Gamma \leq 2$ (Coriat et al. 2011). This means that these 'hard state' data sources used for the radio/X-ray correlation might well have additional low-energy thermal radiation.

In their very recent review, Reynolds & Miller (2013) present a *Swift* survey of all stellar mass black hole binaries which provides a sample of 476 X-ray spectra, which allows studying the disk evolution over a very wide range in flux and temperature. The sensitivity allows observations of accretion disks down to 10^{-3} $L_{\rm Edd}$. It is noteworthy that for the sample with an average luminosity of about 1% Eddington, an accretion disk was detected in 61% of the observations. (For the fit of the hard component a simple power-law model and a Comptonization model were considered.) This sample is the largest data set of such cool accretion disks studied to date.

4. Additional luminosity from a cool inner disk – the effect on the radio/X-ray luminosity correlation

Scattering of soft photons from an underlying disk adds to the scattering of synchrotron and bremsstrahlung photons from the

ADAF. In their analysis of the relation between the photon index and the Eddington ratio, Qiao & Liu (2013) calculated spectra that includes the radiation of an innermost accretion disk. The strength of the inner disk is determined according to possible re-condensation of gas from the corona to the disk below. The re-condensation process works as long as the mass flow rate in the corona is high enough, $\geq 10^{-4}$ to 10^{-3} $L_{\rm Edd}$. The detailed results depend on parameters such as viscosity and the ratio of magnetic pressure to gas pressure. But despite the uncertainties, the calculated spectra show that for mass accretion rates around 2% of the Eddington rate, the underlying disk contributes almost twice as much to the radiation as the coronal flow alone in the 3−9 keV range, and even more in the 0.2−2 keV range (Qiao & Liu, Fig. 3).

To study the effect on the radio/X-ray luminosity relation, we take the values 0.0025, 0.005, and $0.01 \cdot L_{\rm Edd}$ in the following for an assumed additional luminosity caused by the photons of an underlying disk. We compare the resulting increase in luminosity with the observations for H1743-322.

5. Comparison with observations for H1743-322

The upper panel of Fig. 2 shows the observations for H1743-322, together with observations for GX 339-4 and V404 Cyg in the hard state, adopted from the long-term study of Coriat et al. (2011, Fig. 5). The observations for H1743-322 include seven outbursts between 2003 and 2010. Only for the outburst in 2003 do the observations cover a full outburst cycle with rise and decline including the state transitions from hard to soft and back. For the remaining outbursts, with several only in hard state, mainly data during decline are available. Coriat et al. (2011) fitted the high-luminosity data of H1743-322, and in the diagram the fit is shown as a red line. The data were interpreted by the authors as resulting from a radiatively efficient hot flow, LHAF (luminous hot accretion flow, see Yuan 2001).

In the lower panel of Fig. 2, the effect of the contribution from an underlying cool disk is shown. We take the radio luminosity as a tracer of the mass accretion rate $\dot{M}$. For any given mass accretion rate, i.e. for radio luminosity, we consider the increase in the X-ray luminosity $\Delta L_{\rm X}/L_{\rm Edd}$ caused by the photons from the underlying disk. In the figure we show a grid of positions for different additional luminosities (blue lines). We use this grid to determine how much $\Delta L_{\rm X}/L_{\rm Edd}$ is required to find the system at the position of the observed radio/X-ray correlation of H1743-322, the various positions at different radio luminosities given by the red line. (The thin black lines connect the $L_{\rm X}$ values without and with additional luminosity.)

The shape of the red track shows that the required additional contribution of the inner disk increases with the X-ray luminosity, which corresponds to the mass flow rate in the corona, as predicted by the re-condensation model (Meyer et al. 2007). From the comparison of the observations represented by the fit line with the grid of blue lines we find that the values $\Delta L_{\rm X}/L_{\rm Edd}$ needed to obtain the position at the outlier track lie in the range 0.0025 to 0.01 $L_{\rm Edd}$. The lower the original radiation (from scattering the synchrotron and bremsstrahlung photons in the corona), the more prominent the effect of photons from the underlying disk. Such luminosity values are plausible within the context of the re-condensation model, which describes the accretion geometry during that spectral state (Sect. 4).

How can the observations at lower luminosity be understood? For the X-ray luminosities in the range 10^{35} to 10^{36} ergs^{-1}, the radio emission does not change much. Coriat et al. (2011) interpret this range as a range of transition from an LHAF to an ADAF (indicated in their Fig. 7). In our model, re-condensation is only expected for mass accretion rates that are not too low, above 10^{-4} to 10^{-3} $L_{\rm Edd}$, that is for radio luminosities above a few times 10^{19} ergs^{-1} Hz^{-1} (the range indicated on the left side of Fig. 2, lower panel). The X-ray luminosity decreases when the inner disk is not sustained by re-condensation. To show the evolution of the luminosity during an outburst, we mark the data of the outburst 2008a with an additional slash. While the 8.5 GHz radio flux density decreased from 0.23 to 0.13 mJy, the X-ray flux changed from 1.74 to 0.14×10^{-11} erg s^{-1} cm^{-2} (Coriat et al. 2011, Table 1). The lowering to about 1/10 in X-rays within 12 days can be understood as due to the disappearance of the innermost disk.

Since for very low accretion rates, an innermost disk can no longer be sustained by re-condensation, then only one track of radio/X-ray luminosity correlation should be found, a continuation of the upper track down to quiescence, in agreement with observations. At high luminosities, close to those of the transition to the soft state, the mass accretion rate is so high that the effect of an underlying disk becomes unimportant, and also the lower track joins the upper track there.

6. Discussion

6.1. Inner disks and X-ray spectral-timing analysis

Since the inner accretion disk in the hard state is an essential feature of our model for explaining the radio/X-ray luminosity relation, the question arises as to how such an inner disk would be recognized in the spectral-timing analysis. This analysis provides another view of the accretion geometry besides the widely discussed picture of a truncated outer disk, together with an ADAF in the inner region, understood theoretically (Narayan et al. 1998) and confirmed by observations for many LMXBs. Bringing these aspects together might lead to the following picture of the accretion flow.

The observed variability of the power-law continuum in hard state shows spectral-timing properties that can be attributed to accretion rate fluctuations (Kotov et al. 2006). A new spectral analysis technique, the "covariance spectrum method" allows studying how the contributions of the components of the spectrum and variations on different timescales are related (Wilkinson & Uttley 2009; Uttley et al. 2011). Observed spectral time lags of GX 339-4 and other sources make it clear that variations in the disk black body emission substantially lead variations in the power-law emission, which is consistent with the geometry of a soft component arising farther outwards than the hard component. From their analysis of observations of GX 339-4 and Swift J1753.5-0127 on 2004 March 17 and 24, Wilkinson & Uttley concluded that at these times the disk truncation would have been less than 20 Schwarzschild radii. For both observations, the *XMM-Newton* spectra reveal the presence of a cool accretion disk (Miller et al. 2006a,b). In the re-condensation interpretation, this would be in agreement with the weak inner disk and would not impinge on a possible truncation of the standard disk at large radii. The observation for GX 339-4 seems to be in an almost intermediate spectral state as discussed in Sect. 6.2.

If we consider these variations in the outer disk and the consequential variability in the inner hot flow, we expect varying re-condensation that feeds an inner disk. The varying mass flow in the inner disk propagates by diffusing inwards, leading to the observed time lags between outer (cooler) and inner (hotter) regions of this inner disk. The innermost regions of this inner disk provide the most effective photons for Comptonization in the

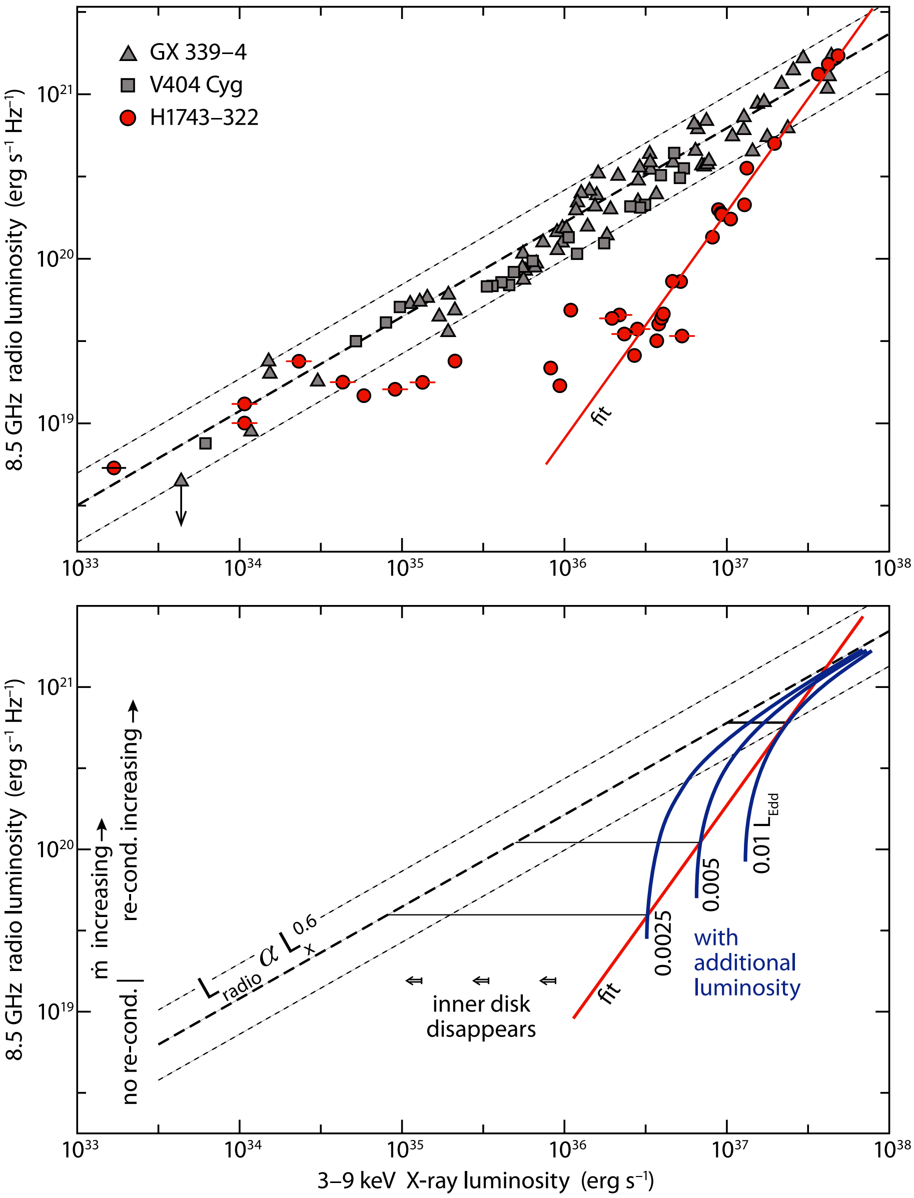

Fig. 2. *Upper panel*: figure adopted from Coriat et al. (2011, Fig. 5): "standard" correlation between radio and X-ray luminosity $L_{\rm radio} \propto L_{\rm X}^{0.6}$, defined by the black hole binaries GX 339-4 and V404 Cyg (dashed lines indicate dispersion) and data for H1743-322, typical of the so-called outliers on the lower track. Red line: fit to the high luminosity data of H1743-322; data for the outburst 2008a marked by horizontal slashes. *Lower panel*: "standard" correlation between radio and X-ray luminosity and fit to the data for H1743-322 as in upper panel; blue lines: X-ray luminosity including additional luminosity caused by the photons of an underlying disk, $\Delta L_{\rm X}/L_{\rm Edd}$ = 0.0025, 0.005 and 0.01); horizontal lines: the increase required for the red line fit to the data of H1743-322.

ADAF/corona. This contribution to the power law besides the synchrotron and bremsstrahlung photons will then vary in phase with the innermost disk photons and show the observed lags to the cooler photons from the outer part of the accretion disk.

6.2. The standard correlation

The upper track of the radio/X-ray correlation is dominated by GX 339-4 and V404 Cyg. The source GX 339-4 was observed many times in hard state. During the long-term campaign of Corbel et al. (2013), quasi-simultaneous radio and X-ray observations in hard state were collected, all corresponding to the standard track. *Swift* and RXTE observations of GX 339-4 in the hard state by Allure et al. (2013) provide information on the different truncations of the accretion disk during three time intervals between 2006 and 2010. Plant et al. (2013) in their recent work found disk truncation, also in GX 339-4, at distances of hundreds of Schwarzschild radii for very low-luminosity/low-accretion rate and near the ISCO for higher accretion rate, the latter representing a hard intermediate state.

According to our suggestion no inner disks should exist during the hard state of sources on the upper track. There is one special observation for GX 339-4: Miller et al. (2006b) find thermal emission from an accretion disk in the low/hard state in the rising phase of the 2004 outburst, interpreted as a weak inner disk. But the flux observed on 2004 March 16/17 is close to the highest values found during the rise. The increasing luminosity is already about 0.05 $L_{\rm Edd}$ (Corbel et al. 2013, Table 1), so that the state seems to be an advanced intermediate spectral state, close to the spectral transition and in the radio/X-ray diagram close to the upper merging of the two tracks. In that situation the contributions of the observed soft photons to the Comptonization of the corona is probably small compared to that of synchrotron and bremsstrahlung photons of the ADAF.

6.3. A systematic difference between the upper and lower track?

The difference between the two tracks seems to require a systemic difference between sources of otherwise similar black hole mass and accretion rates. There appears to be little alternative to locating this difference in the secondary stars and then in their magnetic fields. These fields can reach over and be embedded in the accretion disk and even be concentrated by the accretion flow. Such fields could indeed influence the re-condensation process and thereby the existence and strength of an inner disk. For example, good thermal conduction requires a rather direct magnetic field connection between the disk and the lower regions of the corona above which the material recondenses. Secondly analysis of the re-condensation physics yields a strong dependence on the frictional parameter α in the corona, which will also depend on the magnetic field.

With such a picture in mind, the companion stars of the sources on the two tracks are of interest. Stars with lower mass than the sun have a convective zone in the outer part and are radiative in the inner part, operating a dynamo at the base of the convective zone. More massive stars are radiative in the outer regions, convective inside. The A stars in this group show no strong magnetic fields, but the Ap stars, a subgroup, show strong magnetic fields and possibly have magnetic fields in channels through the adiabatic region, confined in the convective core (Meyer 1993). One expects the same phenomenon in all the more massive stars.

The orbital periods of the companion stars give a rough estimate of the mass of the Roche-lobe filling secondary star. Soleri & Fender (2011) have tested in detail whether, for a sample of 17 black hole binaries, a connection exists between the energy output of the jet and the orbital period and other characteristic parameters such as the size of the disk, the inclination, and the outburst properties. They did not find any association. However, we note that all short-period systems (i.e. secondary stars of low mass) in that sample lie on the lower track (see Corbel et al. 2013, Fig. 9), only the position of XTE J1118+480 is somewhat unclear. The two recent sources XTE J1752-233 (Ratti et al. 2012) and MAXI J1659-152 (Jonker et al. 2012) both are on the lower track and have short orbital periods, 6.8 h and 2.4 h. The sources with long orbital periods (i.e. more massive secondary stars), 26.8 to 155.3 h (periods from Ritter & Kolb 2003), are mainly on the upper track, but a few are on the lower track, as one would expect from the magnetic dichotomy in the more massive stars. It seems surprising that different magnetic field strengths from the secondary stars do not lead to significant scatter around the lower track. This might perhaps indicate that the dominant effect of the magnetic fields on the re-condensation process is the establishment or non-establishment of a good magnetic connection between lower corona and disk, as required for thermal conduction.

The question arises whether the magnetic difference of the sources would not also be mirrored in a difference between the radio luminosity of their jets. However, the cut-off of the lower track and the transition to the upper track at a nearly constant radio luminosity seems to indicate that such an effect is rather small.

6.4. The energy output of the jet affected by an underlying disk?

During the hard to soft transition a drop in radio flux is observed for many sources and attributed to the quenching of the compact (core) jet, such as for GX 339-4 in the high/soft X-ray state by a factor around 25 in comparison with the low/hard state (Fender et al. 1999). Quenching factors that are even much larger, up to several hundred, were found for H1743-322 (Coriat et al. 2011) and 4U 1957+11 (Russell et al. 2011).

The theoretical modelling of jet power can explain the large difference between hard and soft states. Meier (2001) found a jet power from a thin disk to be 100 times weaker than in the ADAF case. The square of the half thickness of the disk enters into the jet power formula. Meyer-Hofmeister et al. (2012) investigated the structure of coronae above accretion disks and the change of ion temperature with a decrease in electron temperature due to Compton cooling. For low accretion rates $\dot{m}$ between 10^{-3} to 10^{-2}, the ion temperature is affected only after a strong decrease in electron temperature. Since the scale height depends on the ion temperature, this means little change in the half thickness of the ADAF/corona in the inner region, from which matter re-condensates into the weak disk. The models and simulations of jet production (Blandford & Znajek 1977; Blandford & Payne 1982; Meier et al. 1997) show that it is the strength of the poloidal component of the magnetic field that is largely responsible for producing the jet. Now, if the accretion geometry with a weak inner disk is only slightly different from a pure ADAF, one expects only a minor effect on the jet power. A reduction of the jet power would lead to lower radio emission for a given X-ray luminosity, which is the same effect on the correlation as from the photons of an inner disk, but probably much weaker.

7. Conclusions

After more and more hard X-ray sources were observed whose radio luminosity was lower than expected from the standard correlation (Gallo et al. 2003) and after it became clear that the two tracks of the radio/X-ray correlation are distinct (Gallo et al. 2012), we suggest that the existence or non-existence of a weak inner disk could provide a physical explanation.

If a weak inner disk exists during the hard spectral state, the Comptonization of the disk photons in the corona provides additional hard X-ray emission. Such a disk is sustained by re-condensation of coronal matter (Meyer et al. 2007; Liu et al. 2007). This shifts the X-ray luminosity to values higher than those expected from an inner ADAF alone. As the radio luminosity of the compact jet emanating from the inner ADAF/corona traces $\dot{m}$ and the X-ray luminosity is increased, the radio/X-ray luminosity correlation becomes steeper, as found for the outlier source H1743-322 displayed in Fig. 2. The red line shows the fit to these high-luminosity data (Coriat et al. 2011), representative of the lower track.

The comparison between our model and the observations yields the following results:

(1) To get the correlation between radio and X-ray flux (described by the red fit line), an additional luminosity of about $0.05L_{\rm Edd}$ from Comptonization of photons from a weak inner disk would be required. This order of magnitude is suggested by computations of spectra that include an inner weak disk in hard spectral state (Qiao & Liu 2013).
(2) The re-condensation model predicts that no inner disk can exist for accretion rates below a certain limit somewhere around 10^{-3} to 10^{-4} $L_{\rm Edd}$. This can help for understanding why the lower track of outliers ends in a transition to the standard track at low luminosity.
(3) At high luminosity where the systems approach the soft state the additional luminosity becomes unimportant and consequently the two tracks merge.

In the radio/X-ray luminosity diagram, the data points for neutron stars lie near the lower track (Soleri & Fender, Fig. 6). It would be interesting to clarify whether their position can be understood as due to the additional luminosity from the neutron star surface that provides photons for a coronal Comptonization. For the chosen sample of neutron stars in their analysis, Migliari & Fender (2006) find a steeper slope in the radio/X-ray relation than the one known for black hole binaries.

A confirmation of our model could come from analysis of spectra in the low energy range, such as *Swift* spectra, with simultaneous radio observations. If further support for the weak inner disks is found, it would be interesting to consider the situation in AGN and consequences for the "fundamental plane" for black hole activity (Merloni et al. 2003).

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