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The X-ray spectral evolution and radio–X-ray correlation in radiatively efficient black-hole sources

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Abstract. We explore X-ray spectral evolution and radio–X-ray correlation simultaneously for four X-ray binaries (XRBs). We find that hard X-ray photon indices, Γ, are anti- and positively correlated to X-ray fluxes when the X-ray flux, $F_{3-9\rm keV}$, is below and above a critical flux, $F_{\rm X,crit}$, which may be regulated by ADAF and disk-corona respectively. We find that the data points with anti-correlation of $\Gamma - F_{3-9\rm keV}$ follow the universal radio–X-ray correlation of $F_{\rm R} \propto F_{\rm X}^{b}$ ($b \sim 0.5 - 0.7$), while the data points with positive X-ray spectral evolution follow a steeper radio–X-ray correlation ($b \sim 1.4$, the so-called 'outliers track'). The bright active galactic nuclei (AGNs) share similar X-ray spectral evolution and radio–X-ray correlation as XRBs in 'outliers' track, and we present a new fundamental plane of $\log L_{\rm R} = 1.59^{+0.28}_{-0.22} \log L_{\rm X} - 0.22^{+0.19}_{-0.20} \log M_{\rm BH} - 28.97^{+0.45}_{-0.45}$ for these radiatively efficient BH sources.

Keywords. accretion, accretion disks - galaxies: jets - X-rays:binaries - galaxies:active

1. Introduction

Quasi-simultaneous radio and X-ray fluxes of X-ray binaries (XRBs) in low hard (LH) state roughly follow a 'universal' non-linear correlation of $F_{\rm R} \propto F_{\rm X}^{b}$ ($b \sim 0.5 - 0.7$). By taking into account the mass of black hole (BH), the relation was extended to active galactic nuclei (AGNs), which is called "fundamental plane" of BH activity. The plane can be described by Merloni *et al.* (2003),

$$\log L_{\rm R} = 0.60^{+0.11}_{-0.11} \log L_{\rm X} + 0.78^{+0.11}_{-0.09} \log M_{\rm BH} + 7.33^{+4.05}_{-4.07}, \quad (1.1)$$

However, in recent years, more and more XRBs were found to lie well outside the scatter of the former universal radio–X-ray correlation. These outliers roughly form a different 'outliers' track, which follow a steeper radio–X-ray correlation with an index of $b \sim 1.4$ as initially found in H1743−322(Coriat *et al.* 2011).

2. Results

We explore hard X-ray spectral evolution in four XRBs (GX 339-4, H1743-322, XTE J1752-223 and Swift J1753-0127) with multiple, quasi-simultaneous radio and X-ray observations. We find that hard X-ray photon indices, Γ, are anti- and positively correlated to X-ray fluxes when the X-ray flux, $F_{3-9\rm keV}$, is below and above a critical flux, $F_{\rm X,crit}$, and the critical Eddington ratio for the transition of anti- and positive $\Gamma - F_{3-9\rm keV}$ correlation is $L_{\rm bol}/L_{\rm Edd} \sim 1\%$ ($L_{\rm bol}$ and $L_{\rm Edd}$ are bolometric luminosity and Eddington luminosity respectively), which are consistent with prediction of advection dominated accretion flow (ADAF) and disk-corona model respectively (Wu & Gu 2008, Cao *et al.* 2014). We further find that the radio–X-ray correlations are also clearly different when

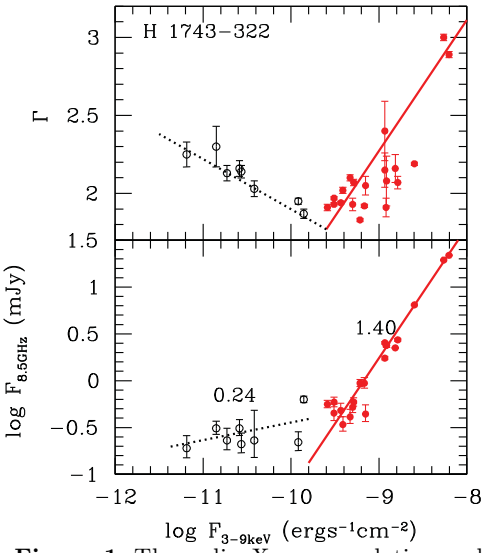

Figure 1. The radio–X-ray correlation and the X-ray spectral evolution for H1743-322.

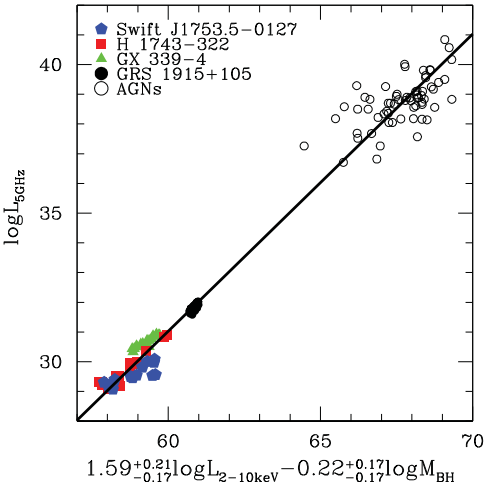

Figure 2. The fundamental plane of black hole activity for radiatively efficient XRBs and AGNs. The solid line is best fit for the whole sample.

the X-ray fluxes are higher and lower than the critical flux that defined by X-ray spectral evolution. The data points with $F_{3-9\rm keV} \gtrsim F_{\rm X,crit}$ have a steeper radio–X-ray correlation ($F_{\rm X} \propto F_{\rm R}^{b}$ and $b \sim 1.1-1.4$), which roughly form the 'outliers' track. However, the data points with anti-correlation of $\Gamma - F_{3-9\rm keV}$ either stay in the universal track with $b \sim 0.6$ or stay in transition track (from the universal to 'outliers' tracks or vice versa). Therefore, our results support that the universal and 'outliers' tracks of radio–X-ray correlations are regulated by radiatively inefficient and radiatively efficient accretion model respectively(see Figure 1 for an example of H1743-322 and more details can be found in Cao *et al.* 2014).

We further compile a sample of bright radio-quiet AGNs and find that their hard X-ray photon indices and Eddington ratios are positively correlated, which is similar to that of 'outliers' of XRBs, where both bright AGNs and 'outliers' of XRBs have $L_{\rm bol}/L_{\rm Edd} \gtrsim 1\%$. The Eddington-scaled radio–X-ray correlation of these AGNs is also similar to that of 'outliers' of XRBs, which has a form of $L_{\rm 5GHz}/L_{\rm Edd} \propto (L_{2-10\rm keV}/L_{\rm Edd})^{c}$ with $c \simeq 1.59$ and 1.53 for AGNs and XRBs respectively. Both the positively correlated X-ray spectral evolution and the steeper radio–X-ray correlation can be regulated by a radiatively efficient accretion flow (e.g., disk-corona). Based on these similarities, we further present a new fundamental plane for 'outliers' of XRBs and bright AGNs in black-hole (BH) mass, radio and X-ray luminosity space,

$$\log L_{\rm R} = 1.59^{+0.28}_{-0.22} \log L_{\rm X} - 0.22^{+0.19}_{-0.20} \log M_{\rm BH} - 28.97^{+0.45}_{-0.45}, \qquad (2.1)$$

with a scatter of $\sigma_{\rm R} = 0.51$dex. This fundamental plane is suitable for radiatively efficient BH sources(more details can be found in Dong *et al.* 2014), while the fundamental plane of Merloni *et al.* (2003) is most suitable for radiatively inefficient BH sources.

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