A disc corona–jet model for the radio/X-ray correlation in black hole X-ray binaries

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ABSTRACT

The observed tight radio/X-ray correlation in the low spectral state of some black hole X-ray binaries implies the strong coupling of the accretion and jet. The correlation of \( L_R \propto L_X^{-0.5} \) was well explained by the coupling of a radiatively inefficient accretion flow and a jet. Recently, however, a growing number of sources show more complicated radio/X-ray correlations, e.g. \( L_R \propto L_X^{-1.4} \) for \( L_X/L_{\text{Edd}} \gtrsim 10^{-3} \), which is suggested to be explained by the coupling of a radiatively efficient accretion flow and a jet. In this work, we interpret the deviation from the initial radio/X-ray correlation for \( L_X/L_{\text{Edd}} \gtrsim 10^{-3} \) with a detailed disc corona–jet model. In this model, the disc and corona are radiatively and dynamically coupled. Assuming a fraction of the matter in the accretion flow, \( \eta \equiv M_{\text{jet}}/M \), is ejected to form the jet, we can calculate the emergent spectrum of the disc corona–jet system. We calculate \( L_R \) and \( L_X \) at different \( \eta \), adjusting \( \eta \) to fit the observed radio/X-ray correlation of the black hole X-ray transient H1743–322 for \( L_X/L_{\text{Edd}} > 10^{-3} \). It is found that always the X-ray emission is dominated by the disc corona and the radio emission is dominated by the jet. We noted that the value of \( \eta \) for the deviated radio/X-ray correlation for \( L_X/L_{\text{Edd}} > 10^{-3} \) is systematically less than that of the case for \( L_X/L_{\text{Edd}} < 10^{-3} \), which is consistent with the general idea that the jet is often relatively suppressed at the high-luminosity phase in black hole X-ray binaries.

Key words: accretion, accretion discs – black hole physics – radio continuum: stars – X-rays: binaries – X-rays: individual: H1743–322.

1 INTRODUCTION

A black hole X-ray binary (BHB) is a gravitationally bound system composed of a black hole and a normal star. BHBs are luminous in X-rays, which is believed to be resulted by accreting the matter of the normal star on to the black hole. According to the X-ray spectral features and the timing properties, two typical spectral states were identified in BHBs, i.e. the high/soft spectral state and the low/hard spectral state (for reviews, see Tanaka & Lewin 1995; Remillard & McClintock 2006). In the high/soft spectral state, the spectrum is dominated by a peak emission around 1 keV, which is believed to be produced by a cool disc extending down to the innermost stable circular orbit (ISCO) of a black hole (Shakura & Sunyaev 1973; Mitsuda et al. 1984; Belloni et al. 2000). The spectral features of the low/hard spectral state are complicated, which are generally thought to be produced by an inner hot accretion flow and an outer truncated cool disc (Rees et al. 1982; Esin, McClintock & Narayan 1997; Esin et al. 2001; McClintock et al. 2001; Yuan, Cui & Narayan 2005; Narayan & McClintock 2008). Recently, some observations indicate that a cool disc may also exist in the region very close to ISCO in the low/hard spectral state (Miller, Homan & Miniutti 2006a; Miller et al. 2006b; Tomisiek et al. 2008; Reis, Fabian & Miller 2010). Meanwhile, the low/hard spectral state is often associated with the production of collimated, relativistic jets, which are quenched in the high/soft spectral state (Fender, Belloni & Gallo 2004).

A correlation between the radio luminosity and X-ray luminosity was found in the low/hard spectral state of BHBs, i.e. \( L_R \propto L_X^b \), with \( b \sim 0.5-0.7 \) (Corbel et al. 2003, 2013; Gallo, Fender & Pooley 2003; Corbel, Koerding & Kaaret 2008). The existing of the radio/X-ray correlation for BHBs is mainly from the observations of two sources, i.e. GX 339–4 and V404 Cyg (Corbel et al. 2013). Yuan & Cui (2005) interpreted this radio/X-ray correlation, i.e. \( L_R \propto L_X^{-0.7} \) for \( L_X \lesssim 10^{-6} L_{\text{Edd}} \) to \( 10^{-3} L_{\text{Edd}} \) (with \( L_{\text{Edd}} = 1.26 \times 10^{38} M/M_\odot \text{ erg s}^{-1} \)) within the framework of a radiatively inefficient accretion flow (RIAF)–jet model, in which a fraction of the matter, \( \eta \), in the accretion flow is assumed to be ejected to form a jet (with \( \eta \equiv M_{\text{jet}}/M \)). In this model, the radio emission was dominated by the self-absorbed synchrotron
emission of a steady, collimated compact jet, and the X-ray emission was dominated by a RIAF via thermal Comptonization process. In the RIAF–jet model, if a constant $\eta$ is assumed for different $M$, the radio luminosity from the jet can be scaled as $L_R \propto \eta M^4$ with $\xi \sim 1$ (e.g. Heinz & Sunyaev 2003), and because of the nature of the advection in RIAF, the X-ray luminosity can be scaled as $L_X \propto M^\xi$ with $q \sim 2$. Then, the predicted radio/X-ray correlation is $L_R \propto L_X^{\xi/q}$ with $\xi/q \sim 0.5$, which is roughly consistent with observations. The RIAF–jet model cannot only interpret the radio/X-ray correlation, but also can explain the broad-band spectral energy distribution (SED) and most of the complex timing features of some black hole X-ray transients, e.g. XTE J1118+480 (Malzac, Merloni & Fabian 2004; Yuan et al. 2005). When BHBs enter the quiescent state, i.e. $L_X \lesssim 10^{-6} L_{\text{Edd}}$, Yuan & Cui (2005) predicted a steeper radio/X-ray correlation of $L_R \propto L_X^{\xi/3}$ within the framework of the RIAF–jet model, in which the radio emission is dominated by the jet, meanwhile the X-ray emission is also dominated by the jet rather than the RIAF. Later, by fitting the SEDs of the black hole X-ray transient GRO J1655–40 and V404 Cyg in the quiescent state, it is found that both the radio emission and the X-ray emission can indeed be explained by the jet (Pszota et al. 2008; Xie, Yang & Yuan 2014). However, due to the very faint emission in the quiescent state, the presence of the radio/X-ray correlation of $L_R \propto L_X^{\xi/3}$ for $L_X \lesssim 10^{-6} L_{\text{Edd}}$ is still controversial (Gallo et al. 2006).

We need to keep in mind the complexities of the observed radio/X-ray correlation. For example, by critically examining the radio/X-ray correlation in a sample of microquasars, Xue & Cui (2007) found that the correlation varied significantly among individual sources, not only in terms of the shape but also of the degree of the correlation. Recently, a statistical analysis of the data led to the new claim of the simple two tracks is also fairly dubious (Coriat et al. 2011). Anyhow, so far, a growing number of sources have been discovered with a steeper radio/X-ray correlation, namely, $L_R \propto L_X^{-1/4}$, during $L_X \gtrsim 10^{-3} L_{\text{Edd}}$ [e.g. IGR J17497–2821 (Rodriguez et al. 2007), XTE J1650–500 (Corbel et al. 2004), Swift J1753.5–0127 (Soleri et al. 2010)]. The study of the radio/X-ray correlation of $L_R \propto L_X^{-1/4}$ for $L_X \gtrsim 10^{-3} L_{\text{Edd}}$ is the purpose of this work. By collecting the archive quasi-simultaneous radio and X-ray data between 2003 and 2010, Coriat et al. (2011) comprehensively studied the relationship between the radio luminosity and X-ray luminosity of the black hole X-ray transient H1743–322. It is found that during a high-luminosity phase, corresponding to $L_X/L_{\text{Edd}} \sim 10^{-3}$ to $10^{-1}$, H1743–322 follows the radio/X-ray correlation with a steeper slope of $b \sim 1.4$. While during a low-luminosity phase, corresponding to $L_X/L_{\text{Edd}} \lesssim 10^{-5}$, H1743–322 follows the radio/X-ray correlation with a slope of $b \sim 0.6$. For $L_X/L_{\text{Edd}}$ between $10^{-3}$ and $10^{-1}$, it is probably corresponding to a transition region between the two correlations.

The change of the radio/X-ray correlation from the low-luminosity phase to the high-luminosity phase in H1743–322 may imply either the change of the properties of the accretion flow or the change of the different coupling in the accretion flow and jet, e.g. the change of the dependence of the fraction of the matter $\eta$ ejected to form the jet on the mass accretion rate $M$. The sources with the radio/X-ray correlation of $L_R \propto L_X^{-1/4}$ could be considered as a X-ray loud hypothesis, i.e. for a given radio luminosity, the simultaneous X-ray luminosity of the track with $b \sim 1.4$ is higher than that of the track with $b \sim 0.5$–0.7, or in turn could be considered as a radio quiet hypothesis, i.e. for a given X-ray luminosity, the simultaneous radio luminosity of the track with $b \sim 1.4$ is lower than that of the track with $b \sim 0.5$–0.7. In both hypotheses, the radio emission is dominated by the self-absorbed synchrotron emission of the steady, collimated compact jet, and the X-ray emission is dominated by the accretion flow. The main difference of the two hypotheses is the different dependence of $\eta$ on $M$. In the X-ray loud hypothesis, if a constant $\eta$ is assumed for different $M$, for a given radio luminosity, the higher X-ray luminosity of the track with $b \sim 1.4$ is probably resulted by the transition of the accretion flow from a RIAF to a radiatively efficiently accretion flow, e.g. a disc corona system by Haardt & Maraschi (1991, 1993), Di Matteo, Celotti & Fabian (1999), Liu, Mineshige & Shibata (2002a), Liu, Mineshige & Ohsuga (2003), Merloni & Fabian (2002), Cao (2009) and Huang, Wu & Wang (2014), or a luminous hot accretion flow by Yuan (2001), Xie & Yuan (2012) and Ma (2012). Meyer-Hofmeister & Meyer (2014) proposed that recondensation of gas from the corona into an inner disc can provide additional soft photons for Comptonization, which leads to a higher X-ray luminosity compared to the unchanged radio emission. In the radio quiet hypothesis, a varied $\eta$ is assumed for different $M$. As suggested by Coriat et al. (2011), if there is a linear dependence of $\eta$ on $M$, i.e. $\eta \propto M$, the predicted radio/X-ray correlation should be $L_R \propto L_X^q$. Because for RIAF $q \sim 2$, the predicted slope of the radio/X-ray correlation is also roughly close to the track with $b \sim 1.4$. However, theoretically, the dependence of the correlation on $M$ is unclear (e.g. Pe'er & Casella 2009), further studies are still needed to put constraints on the relation between $\eta$ and $M$.

Observationally, there is evidence of a coupling of the hot plasma and the jet in both BHBs and active galactic nuclei (AGN), i.e. the coupling of the disc corona and jet at high mass accretion rates and the coupling of the RIAF and jet at low mass accretion rates (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004; Zdziarski et al. 2011; Wu et al. 2013). Meanwhile, theoretically, for $M \gtrsim \alpha^2 M_{\text{Edd}}$ (with $\alpha$ the viscosity parameter, $M_{\text{Edd}} = 1.39 \times 10^{18} M\odot$ g s$^{-1}$), the accretion flow will transit from a RIAF to a disc corona system, which has been comprehensively studied by many authors, e.g. Meyer, Liu & Meyer-Hofmeister (2000a,b), Liu et al. (2002b) and Qiao & Liu (2009, 2010, 2013) within the framework of the disc evaporation model, or by Narayan & Yi (1995), Abramowicz et al. (1995) and Mahadevan (1997) within the framework of the RIAF solution.

Consequently, in this paper, we propose a disc corona–jet model to explain the radio/X-ray correlation of $L_R \propto L_X^{-1/4}$ during the high-luminosity phase $L_X/L_{\text{Edd}} \gtrsim 10^{-3}$, in which a fraction of the matter, $\eta$, in the corona is assumed to be ejected to form the jet. So far, the theoretical understanding of the jet formation is poor. Specifically, it is difficult to put constraints on the dependence of $\eta$ on $M$ in our model, so we set $\eta$ as an independent parameter on $M$ to fit the observations. As an example, by fitting the observed radio/X-ray correlation during the high-luminosity phase of black hole X-ray transient H1743–322 for $L_X/L_{\text{Edd}} > 10^{-3}$, we found that $\eta$ is weakly dependent on $M$, and the mean fitting result of $\eta$ is $\sim 0.57$ per cent. The derived relatively smaller fitting value of $\eta$ supports the general idea that the jet is often suppressed at the high-luminosity phase of BHBs. The disc corona–jet model is briefly described in Section 2. The numerical results are presented in Section 3. Some comparisons with observations are shown in Section 4. Discussions are in Section 5, and the conclusions are in Section 6.
2 THE MODEL

2.1 Accretion flows

The accretion flows adopted here is a geometrically thin disc enclosed by a geometrically thick, hot corona around a central black hole (Liu et al. 2002a, 2003). The disc is a standard Shakura & Sunyaev (1973) disc, which is tightly coupled with the plane-parallel corona. Magnetic fields are assumed to be generated by dynamo action. As a result of Parker instability, magnetic flux loops continuously emerge from the disc to the corona and reconnect with other loops. In this way, the accretion energy taken from the thin disc is released in the corona as thermal energy and eventually emitted away mostly in X-ray band via inverse Compton scattering. The density of the corona is determined by an energy balance between the downward heat conduction and mass evaporation in the chromospheric layer. A detailed description of the model can be found in Liu et al. (2002a, 2003). The equations describing these processes in the corona are as follows:

\[
\frac{B^2}{4\pi} V_A \approx \frac{4kT}{m_e c^2} \tau^* U_{\text{rad}}, \tag{1}
\]

\[
k_0 T^{1/2} \approx \frac{\tau}{\tau^*} \text{nk} T \left(\frac{kT}{m_i}\right)^{1/2}, \tag{2}
\]

where \(T\) is the coronal temperature, \(n\) is the coronal number density, \(B\) is the strength of magnetic field, \(U_{\text{rad}}\) is the energy density of the soft photon field for Compton scattering, \(V_A = \sqrt{\frac{\mu_0 B}{\pi n}}\) is the Alfvén speed, \(\ell\) is the length of magnetic loop, \(\tau^*\) is the effective optical depth, defined as \(\tau^* \equiv \tau \text{se} n \tau \ell\) with \(\tau \sim 1\). Other constants have their standard meanings. From equations (1) and (2), the temperature \(T\) and density \(n\) in the corona can be determined for a given magnetic field \(B\) and radiation field \(U_{\text{rad}}\), and then the radiative spectrum can be calculated out.

For a coupled disc and corona system, the magnetic field is derived from an equipartition of gas pressure and magnetic pressure in the disc, i.e. \(B \equiv \frac{\mu_0 H_c}{\pi R^2} = 1\). The soft photons (\(U_{\text{rad}}\)) are composed of intrinsic disc radiation \(U_{\text{rad}}^{\text{disc}}\) and the reprocessed radiation of backward Compton emission of the corona \(U_{\text{rad}}^{\text{corona}}\). With energy transporting to the corona by the magnetic field, the disc is expected to be gas pressure dominant. Thus, the magnetic field and soft photon field can be expressed as functions of black hole mass, accretion rate and distance:

\[
B = 2.86 \times 10^3 \alpha_{\text{in}}^{-9/20} \beta^{-1/2} m^{-9/20} [\text{m}_i \phi(1 - f)]^{1/2} r_1^{-51/40} \text{G}, \tag{3}
\]

\[
U_{\text{rad}}^{\text{disc}} = \frac{aT_{\text{eff}}^4}{\pi} = \frac{4}{3} \frac{3GM\dot{M}(1 - f)\phi}{8\pi R^3}, \tag{4}
\]

\[
U_{\text{rad}}^{\text{corona}} = 0.4\lambda_a U_B, \tag{5}
\]

where \(m\), \(\text{m}_i\), \(\alpha_{\text{in}}\), \(\beta\) and \(r_1\) are the mass of black hole, the accretion rate, the viscosity parameter, the equipartition factor and the distance, respectively, scaled by \(\text{M}_\odot\), \(0.1\) \(\dot{M}_{\text{Edd}}\), \(0.1\), \(1\) and \(10R_8\), \(\phi = 1 - \left(R_c/R_8\right)^2\) and \(R_c = 3R_8\) is adopted as the ISCO of a non-rotating black hole \(R_c \approx 2.95 \times 10^8 M_\odot / M_\odot\). \(\lambda_a\) is a factor introduced for the evaluation of the seed field in Haardt & Maraschi (1991, 1993), which is around 1 in order of magnitude. Here the energy fraction dissipated in the corona, \(f\), is not a free parameter but can be expressed as

\[
f = \frac{F_{\text{cor}}}{F_{\text{tot}}} = \left(\frac{B^2}{4\pi} V_A \right) \left(\frac{3GM\dot{M}\phi}{8\pi R^3}\right)^{-1}, \tag{6}
\]

Combing equations (1)–(6), we get a solution of the corona above a gas-pressure-dominated disc in the case of \(U_{\text{rad}}^{\text{corona}} \gg U_{\text{rad}}^{\text{disc}}\):

\[
T = 3.86 \times 10^9 \frac{\alpha_{\text{in}}^{9/20}}{\beta^{1/2}} \left[\frac{\text{m}_i \phi(1 - f)}{r_1^{51/40} \dot{M}_{\text{Edd}}}ight]^{1/2} m^{-1/30} \text{K}, \tag{7}
\]

\[
n = 1.61 \times 10^8 \frac{\alpha_{\text{in}}^{9/20}}{\beta^{1/2}} \left[\frac{\text{m}_i \phi(1 - f)}{r_1^{51/40} \dot{M}_{\text{Edd}}}ight]^{1/2} m^{-39/40}, \tag{8}
\]

\[
f = 3.73 \times 10^4 \left(1 - f\right) \frac{1}{10^{0.1} \text{erg cm}^{-3}} \times \left(\frac{\alpha_{\text{in}} \phi(1 - f)}{r_1^{51/40}}\right)^{1/8} \frac{1}{10^{0.1} \text{erg cm}^{-3}} \times \left(\frac{\alpha_{\text{in}} \phi(1 - f)}{r_1^{51/40}}\right)^{3/8}. \tag{9}
\]

Given the values of the input parameters \(m\), \(\alpha_{\text{in}}\), \(\beta\) and the initial values of \(\lambda_a\) and \(\lambda_a\), we can solve equation (9) for \(f\). Then \(T\) and \(n\) are solved from equations (7) and (8). The effective temperature of the soft photos \(T_{\text{eff}}\),

\[
\sigma T_{\text{eff}}^4 = \frac{3GM\dot{M}(1 - f)}{8\pi R^3}, \tag{10}
\]

can also be calculated by combing equations (3) and (5) (with albedo always being assumed to be zero in our calculations). With \(T\), \(n\) and \(T_{\text{eff}}\), the spectra of the disc–corona system can be calculated by Monte Carlo simulation.

In our detailed calculations, we also take into account the influences of \(\lambda_a\), \(\lambda_a\) and the length of magnetic loops. Since the corona temperature \(T\), density \(n\) and energy fraction \(f\) do not sensitively depend on \(\lambda_a\) and \(\lambda_a\) (see equations 7–9), and the value of \(\lambda_a\) and \(\lambda_a\) should be \(\sim 1\) in order of magnitude, the corona spectra cannot be significantly affected by the chosen value of \(\lambda_a\) and \(\lambda_a\). Nevertheless, we repeat the Monte Carlo simulation by adjusting the value of \(\lambda_a\) and \(\lambda_a\). We find a set of reasonable value for \(\lambda_a\) and \(\lambda_a\), even though the downward-scattered luminosity is equal to the seed luminosity and the upward-scattered luminosity is equal to the released gravitational energy. In this way we find a self-consistent solution of the disc–corona system and get the corresponding emergent spectrum. We test the effect of the length of magnetic loop \(\ell\) on the emergent spectrum, it is found that the emergent spectrum is very weakly dependent on \(\ell\). So in our model, \(\ell\) is not a free parameter, and we set \(\ell = 10R_8\) throughout the calculations. For the detailed description of the Monte Carlo simulation, one can also refer to Liu et al. (2003).

2.2 Coupled disc corona-jet model

The calculation of jet emission is based on the internal shock scenario as described in Yuan et al. (2005). In the disc corona–jet model, a small fraction of the matter in the accretion flow, i.e. \(\dot{M}_j = \eta \dot{M}\), is assumed to be ejected to form the jet. In this work, a conical geometry is considered for the jet, and the half opening angle of the jet is fixed at \(\varphi = 0.1\). Changing the value of \(\varphi\) will lead to a change of the density of the jet, however, this effect can be absorbed by the mass accretion rate. The bulk Lorentz factor of the jet is fixed at \(\Gamma_{\text{jett}} = 1.2\), which is well consistent with the typically observed value of the jet in the low/hard spectral state of BHBs (e.g. Fender 2006). Within the jet, internal shock is produced due to the collision of the shells with different velocities. The internal shocks will accelerate a small fraction of the electrons to be a power-law energy distribution with index \(p\). We fix \(p = 2.1\) in the calculations as suggested by Zhang, Yuan & Chakty (2010) for fitting the SEDs of
three black hole X-ray transients J1753.5−0127, GRO J1655−40 and XTE J1720−318. The two parameters, $L_x$ and $L_B$, describing the ratio of the energy of the accelerated electrons and the amplified magnetic field to the shock energy in the shock front are fixed at $L_x = 0.04$ and $L_B = 0.02$, respectively, which are consistent with the observations of gamma-ray bursts (GRB) afterglows (e.g. Panaitescu & Kumar 2001, 2002). Because the Compton scattering optical depth of the jet is small, only synchrotron emission is considered in the calculation (Markoff, Falcke & Fender 2001).

3 NUMERICAL RESULT

We calculate the emergent spectra of the disc corona–jet model around a stellar mass black hole with mass $M$ when the parameters including $M$, $\alpha$ and $\eta$ are specified. In this paper, we fix the black hole mass at $M = 10M_\odot$, assuming a typical viscosity parameter $\alpha = 0.3$, and a constant $\eta$ for different $M$.

Given $\eta = 0.2$ per cent, the emergent spectra are plotted in the left-hand panel of Fig. 1 for different mass accretion rates, i.e. from the bottom up $M = 0.02$, 0.05, 0.1, 0.3 and 0.5 $M_{\text{Edd}}$. The solid lines are the total emergent spectra, and the dotted lines are the emergent spectra from the jets. From the left-hand panel of Fig. 1, we can clearly see that X-ray emission is dominated by the disc–corona system and the radio emission is dominated by the jet for the mass accretion rates from $M = 0.02$ to 0.5 $M_{\text{Edd}}$. Based on the emergent spectra, we calculate the radio luminosity $L_{8.5\,\text{GHz}}$ and the X-ray luminosity $L_{2-10\,\text{keV}}$ for different $M$. The best-fitting linear regression for the correlation between $L_{8.5\,\text{GHz}}/L_{\text{Edd}}$ and $M$ can be expressed as

$$\frac{L_{8.5\,\text{GHz}}}{L_{\text{Edd}}} = A(\eta) \left( \frac{M}{M_{\text{Edd}}} \right)^{\xi(\eta)} ,$$

(11)

where $A(\eta) = 0.2$ per cent $= 10^{-8.47}$ and $\xi(\eta) = 0.2$ per cent $= 1.42$. The best-fitting linear regression for the correlation between $L_{2-10\,\text{keV}}/L_{\text{Edd}}$ and $M$ can be expressed as

$$\frac{L_{2-10\,\text{keV}}}{L_{\text{Edd}}} = 10^{-1.23} \left( \frac{M}{M_{\text{Edd}}} \right)^q ,$$

(12)

where $q = 1.06$, which is roughly consistent with a radiatively efficient accretion flow with $L_X \propto M$ (e.g. Haardt & Maraschi 1991, 1993). Combing equations (11) and (12), we can derive that

$$\frac{L_{8.5\,\text{GHz}}}{L_{\text{Edd}}} = A(\eta) 10^{8.47} \left( \frac{L_{2-10\,\text{keV}}}{L_{\text{Edd}}} \right)^{\xi(\eta)/q} ,$$

(13)

where $\xi(\eta)/q = 0.2$ per cent $\approx 1.35$ and $A(\eta) 10^{8.47} |q| = 10^{-6.8}$. The derived slope of radio/X-ray correlation from the disc corona–jet model is steeper than that of the RIAF–jet model, i.e. for a fixed X-ray luminosity, the increase of the radio luminosity of the disc–corona system is more quick than that of the RIAF. One of the reasons is that, for a given radio luminosity, due to the nature of the high radiative efficiency, the simultaneous X-ray luminosity predicted by the disc–corona system is intrinsically higher than that of the RIAF. Moreover, because the X-ray luminosity of RIAF is roughly $L_X \propto M^2$, and the X-ray luminosity of the disc–corona system is roughly $L_X \propto M^{1.06}$, for a fixed radio luminosity, the increase of the X-ray luminosity of the RIAF is more quick than that of the disc–corona system, which in turn is equivalent to the case, i.e. for a fixed X-ray luminosity, the increase of the radio luminosity of the disc–corona system is more quick than that of the RIAF.

In order to check the effects of $\eta$ on the radio/X-ray correlation, we assume another constant $\eta$ for different $M$, i.e. $\eta = 0.5$ per cent, to calculate the emergent spectra for comparisons with that of $\eta = 0.2$ per cent. The emergent spectra are shown in the right-hand panel of Fig. 1. The best-fitting linear regression for the correlation between $L_{8.5\,\text{GHz}}/L_{\text{Edd}}$ and $M$ can be expressed as $L_{8.5\,\text{GHz}}/L_{\text{Edd}} = A(\eta)(M/M_{\text{Edd}})^{\xi(\eta)}$ with $A(\eta)_{\eta=0.5} = 10^{-7.04}$ and $\xi(\eta)_{\eta=0.5} = 1.40$, and the best-fitting linear regression for the correlation between $L_{2-10\,\text{keV}}/L_{\text{Edd}}$ and $M$ can be expressed as $L_{2-10\,\text{keV}}/L_{\text{Edd}} = 10^{-1.23} (M/M_{\text{Edd}})^q$ with $q = 1.06$. Then, the predicted radio/X-ray correlation is $L_{8.5\,\text{GHz}}/L_{\text{Edd}} = A(\eta) 10^{8.47} \left( L_{2-10\,\text{keV}}/L_{\text{Edd}} \right)^{\xi(\eta)/q}$ with $A(\eta) 10^{8.47} |q| = 10^{-6.3}$ and $\xi(\eta)/q = 0.5$ per cent $\approx 1.32$. Roughly, it is clearly shown that a systematic increase of the fraction of the matter ejected to the jet leads the radio flux to a systematic increase, however, does not change the slope of the radio/X-ray correlation much.
In the above calculations, we assume that $\eta$ is a constant for different $M$ to produce the radio/X-ray correlation. However, actually the dependence of $\eta$ on $M$ is unclear, so $\eta$ will be set as an independent parameter on $M$ to fit the detailed observations in the next section.

4 APPLICATION TO BLACK HOLE X-RAY TRANSIENT H1743–322

H1743–322 is an X-ray transient discovered in 1977 (Doxsey et al. 1977; Kaluzienski & Holt 1977), then detected again by the International Gamma-ray Astrophysics Laboratory (INTEGRAL) during the burst in 2003. H1743–322 is well studied in both radio and X-ray band. By comparing both the spectral features and the timing properties of H1743–322 to the well-studied black hole X-ray transient XTE J1550–564, McClintock et al. (2009) argued that H1743–322 is a accreting black hole. The black hole mass of H1743–322 is inferred to be $\sim 10 M_\odot$ (e.g. Steiner, McClintock & Reid 2012). Coriat et al. (2011) analysed all the archive data of H1743–322 observed by RXTE between 2003 January 1 and 2010 February 13, meanwhile the authors conducted quasi-simultaneous ($\Delta t \lesssim 1$ d) radio observations through Telescope Compact Array (ATCA), Compact Array Broad-band Backend (CABB) and collected the observational data of Very Large Array (VLA) in the literature.

Based on the data of H1743–322 from Coriat et al. (2011), we plot the relation between $L_{\text{3–9 keV}}/L_{\text{Edd}}$ and $L_{\text{8.5 GHz}}/L_{\text{Edd}}$ with the red sign ‘∗’ in the right-hand panel of Fig. 2. For $L_{\text{3–9 keV}}/L_{\text{Edd}} > 10^{-3}$, the best-fitting linear regression for the correlation between $L_{\text{3–9 keV}}/L_{\text{Edd}}$ and $L_{\text{8.5 GHz}}/L_{\text{Edd}}$ is as follows:

$$\left( \frac{L_{\text{8.5 GHz}}}{L_{\text{Edd}}} \right) = 10^{3.9} \left( \frac{L_{\text{3–9 keV}}}{L_{\text{Edd}}} \right)^{1.39}. \quad (14)$$

This is plotted in the right-hand panel of Fig. 2 with the dotted line. Fixing $M = 10 M_\odot$, $\alpha = 0.3$, we calculate the radio luminosity $L_{\text{8.5 GHz}}$ and X-ray luminosity $L_{\text{3–9 keV}}$ for different $M$, adjusting $\eta$ to fit equation (14). It is found that $\eta$ is very weakly dependent on $M$, i.e. for $M = 0.02 M_{\text{Edd}}$, $\eta = 0.54$ per cent; for $M = 0.05 M_{\text{Edd}}$, $\eta = 0.52$ per cent; for $M = 0.1 M_{\text{Edd}}$, $\eta = 0.57$ per cent; for $M = 0.3 M_{\text{Edd}}$, $\eta = 0.62$ per cent; for $M = 0.5 M_{\text{Edd}}$, $\eta = 0.62$ per cent.

The mean fitting value of $\eta$ is $\sim 0.57$ per cent. The thick solid line in the right-hand panel of Fig. 2 is the model line. The corresponding emergent spectra with mass accretion rates are plotted in the left-hand panel of Fig. 2. Yuan & Cui (2005) fitted the radio/X-ray correlation of $L_R \propto L_X^{\delta}$ for $L_X \approx 10^{-6} L_{\text{Edd}}$ to $\approx 10^{-3} L_{\text{Edd}}$ within the framework of the RIAF–jet model. They found that the fitting result was very sensitive to a parameter $\delta$, which denotes the fraction of the viscosity dissipated energy directly heating the electrons in the RIAF. For $\delta = 0.5$, they found that $\eta$ was highly dependent on $M$, decreasing from $\eta \sim 10$ to $\sim 1$ per cent with mass accretion rate from $M \sim 10^{-3} M_{\text{Edd}}$ to $10^{-2} M_{\text{Edd}}$. For a smaller value of $\delta = 0.01$, they found that $\eta$ was nearly a constant with $M$, i.e. $\eta \sim 1$ per cent.

Indeed, we have tested the value of $\eta$ for H1743–322 during the phase $L_X/L_{\text{Edd}} \lesssim 10^{-3}$ within the framework of RIAF–jet model. We found $\eta \sim 10$ per cent. It is clear that the fitting value of $\eta$ from the RIAF–jet model for the low-luminosity phase is systematically higher than that of the fitting value of $\eta$ from the disc corona–jet model for the high-luminosity phase, which is consistent with the general idea that the jet is often relatively suppressed at the high-luminosity phase in BHBs (Fender et al. 2004).

In the present jet model, besides the mass rate in the jet $M_{\text{jet}}$, there are still three parameters, which can affect the emission of the jet, i.e. the power-law energy distribution index of the accelerated electrons $p$, the ratio of the energy of the accelerated electrons and the amplified magnetic field to the shock energy, and $\eta$ in the ratio of the energy of the accelerated electrons and the amplified magnetic field to the shock energy, $\epsilon_e$ and $\epsilon_B$. In this work, $p = 2.1$, $\epsilon_e = 0.04$ and $\epsilon_B = 0.02$ are fixed, respectively. By modelling the broadband emission of the afterglow of eight GRBs, Panaitescu & Kumar (2001) derived that $p = 1.87 \pm 0.51$, $\epsilon_e = 0.062 \pm 0.045$ and $\log \epsilon_B = -2.4 \pm 1.2$. Yuan et al. (2005) fitted the multiband wavelength observations of XTE J1118+480 with RIAF–jet model, in which the best-fitting results are $p = 2.24$, $\epsilon_e = 0.06$ and $\epsilon_B = 0.02$, respectively. Based on RIAF–jet model, Zhang et al. (2010) fitted the...
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Figure 3. Emergent spectra of the jet for different parameters. In the left-hand panel, \(M = 10 M_\odot\), \(\dot{M} = 0.5 \dot{M}_{\text{Edd}}, \eta = 0.5\) per cent, \(p = 2.1\) and \(\epsilon_\beta = 0.02\) are fixed, and from the bottom up, \(\epsilon_e = 0.01, 0.04, 0.08\) and 0.1, respectively. In the right-hand panel, \(M = 10 M_\odot\), \(\dot{M} = 0.5 \dot{M}_{\text{Edd}}, \eta = 0.5\) per cent, \(p = 2.1\) and \(\epsilon_e = 0.04\) are fixed, and from the bottom up, \(\epsilon_\beta = 0.01, 0.02, 0.05\) and 0.1, respectively.

Simultaneous multiwavelength observations of three black hole X-ray transients J1753.5−0127, GRO J1655−40 and XTE J1720−318. It is found that the best-fitting results in J1753.5−0127 are \(p = 2.1, \epsilon_e = 0.04\) and \(\epsilon_\beta = 0.02\), in GRO J1655−40 are \(p = 2.1, \epsilon_e = 0.06\) and \(\epsilon_\beta = 0.02\), and in XTE J1720−318 are \(p = 2.1, \epsilon_e = 0.06\) and \(\epsilon_\beta = 0.08\). It has been tested that the different values of \(p\) have very minor effects on the radio emission, however, have significant effects on the X-ray emission (Ozel, Psaltis & Narayan 2000; fig. 4 in Yuan, Quataert & Narayan 2003). Because of the X-ray emission is always dominated by the emission of disc and corona, the change of \(p\) in an observationally reasonable range will not change our results. Throughout the calculation \(p = 2.1\) is fixed. We test the effects of \(\epsilon_e\) and \(\epsilon_\beta\) on the jet emission. In the left-hand panel of Fig. 3, fixing \(M = 10 M_\odot\), \(\alpha = 0.3\), \(\dot{M} = 0.5\), \(\eta = 0.5\) per cent, \(p = 2.1\) and \(\epsilon_\beta = 0.02\), we plot the emergent spectra of jet for \(\epsilon_e = 0.01, 0.04, 0.08, 0.1\), respectively. It is found that \(\epsilon_e\) is sensitive to the X-ray emission, and insensitive to the radio emission. However, in the observationally inferred range of \(\epsilon_e \sim 0.01–0.1\), it is clear that the X-ray emission is still dominated by the disc and corona instead of the jet, so the change of \(\epsilon_e\) will not change our results (see the right-hand panel of Fig. 1 for comparison). Throughout the calculation \(\epsilon_e = 0.04\) is fixed. In the right-hand panel of Fig. 3, fixing \(M = 10 M_\odot\), \(\alpha = 0.3\), \(\dot{M} = 0.5\), \(\eta = 0.5\) per cent, \(p = 2.1\) and \(\epsilon_e = 0.04\), we plot the emergent spectra of jet for \(\epsilon_\beta = 0.01, 0.02, 0.05, 0.1\), respectively. It is found that, increasing the value of \(\epsilon_\beta\) will increase the radio emission, and nearly does not change the X-ray emission. As discussed in Section 3.1, an increase of \(M_\text{jet}\) will also increase the radio emission. So detailed spectral fitting are needed to disentangle the effects of \(\epsilon_e\) and \(M_\text{jet}\) on the jet emission, which is beyond the scope of the present paper. In order to compare with other works for the fraction of the matter ejected to form the jet in the low-luminosity phase (e.g. Yuan & Cui 2005), we take the same value of \(\epsilon_\beta = 0.02\) as adopted in Yuan & Cui (2005). In a word, although the parameters in the jet are uncertain, we still can conclude that the jet is relatively suppressed at the high-luminosity phase in BHBs.

The mechanism of jet formation is unclear. Narayan & McClintock (2012) collected a small sample composed of five black hole X-ray transients with precise spin measurements. Meanwhile the authors estimated the ballistic jet power using the data at 5 GHz radio observations. It is found that the estimated jet power is correlated with the square of \(a_*\) (with \(a_* = cJ/GM^2, J\) is angular momentum of the black hole), which is very close to the theoretical scaling derived by Blandford & Znajek (1977). However, by separately considering the ballistic jet and the hard steady jet, Fender, Gallo & Russell (2010) found that there is no evidence for the correlation between the jet power and the black hole spin. Recently, an interesting paper argued that the jet formation may be correlated with the hot plasma, namely, the jet power is correlated with the RIAF when the Eddington ratio is less than \(\sim 1\) per cent and the jet power is correlated with the hot corona above the cool disc when the Eddington ratio is greater than \(\sim 1\) per cent (Wu et al. 2013). Our study may put some constrains on the mechanism of jet formation, i.e. by suggesting that the relative strength of the jet power may be inversely correlated with the Eddington ratio in an accreting black hole (e.g. Körding, Falcke & Markoff 2002; Fender, Gallo & Jonker 2003).

As a comparison, in the right-hand panel of Fig. 2, we also plot the relation between \(L_{9\text{keV}}/L_{\text{Edd}}\) and \(L_{8.5\text{GHz}}/L_{\text{Edd}}\) for GX 339–4 with the sign of green ‘△’ and V404 Cyg with the sign of orange ‘□’. For \(L_X > 10^{34} L_{\text{Edd}}\), the radio/X-ray correlation with \(L_{8.5\text{GHz}} \propto L_{9\text{keV}}^{0.6}\) is expected to be interpreted within the framework of the RIAF–jet model, as suggested for the black hole X-ray transient XTE J1118+480. However, how to justify the existence of the RIAF at the high-luminosity phase? Qiao & Liu (2009) studied the effect of the viscosity parameter \(\alpha\) on the critical mass accretion rate for the transition from a RIAF to a disc corona system within the framework of the disc evaporation model. The authors derived that \(M_{\text{crit}} \propto \alpha^{2.34} \dot{M}_{\text{Edd}}\), i.e. a larger value of \(\alpha\) can increase the critical mass accretion rate for the existence of the RIAF. A similar result to the critical mass accretion rate for the existence of the RIAF, i.e. \(M_{\text{crit}} \propto \alpha^{2} \dot{M}_{\text{Edd}}\) was also derived from the RIAF solution (Narayan & Yi 1995; Mahadevan 1997). By summarizing the observational data of dwarf nova outbursts, outbursts of X-ray transients, variability in AGN and so on, King, Pringle & Livio (2007) inferred that the value of \(\alpha\) is in the range of \(\sim 0.1–0.4\). Extremely, Narayan (1996) took \(\alpha = 1\) to explain the BHB systems with high transition luminosities. Theoretical understandings for the viscosity have been studied for many years since the pioneering work by Shakura & Sunyaev (1973) (Balbus & Hawley 1991; Hawley, Gammie &
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5 DISCUSSION

In this work, we proposed a disc corona–jet model to explain the observed radio/X-ray correlation of $L_R \propto L_X^{-1.4}$ for $L_X/L_{\rm Edd} \gtrsim 10^{-3}$ in BHBs. We noted that a similar disc corona–jet model was also proposed for explaining this radio/X-ray correlation, in which the X-ray emission is also dominated by the disc and corona, and the radio emission is dominated the jet (Huang et al. 2014). Both in our work and Huang et al. (2014), for the disc–corona model, it is assumed that the magnetic field is generated by dynamo action in the accretion disc, then due to buoyancy, the magnetic loops emerge from the accretion disc into the corona and reconnect with other loops. In this way the accretion energy is released in the corona as thermal energy and eventually emitted away via inverse Compton scattering. By studying the energy balance of the disc and the corona, Huang et al. (2014) solved the structure of the cold accretion disc. However, they cannot self-consistently determine the temperature of the corona $T$ and the Compton scattering optical depth $\tau$, which are two very important quantities for determining the shape of the Compton emergent spectrum. Theoretically, $T$ and $\tau$ should be solved independently for determining the Compton emergent spectrum. In Huang et al. (2014), it is argued that the observationally inferred value of $\tau$ is in the range of $\sim 0.1$–$0.8$, then through their calculation, $\tau = 0.5$ is fixed to solve $T$ for fitting this radio/X-ray correlation. In our model, we do not fix the value of $\tau$. We performed self-consistent Monte Carlo simulation to treat the structure of the disc–corona system. The fraction of the dissipated energy in the corona $f$, the temperature of the corona $T$ and the Compton scattering optical depth $\tau$ can be self-consistently determined, which are important advantages of our model.

We note that in our model, currently in order to simplify the calculation of the complex interaction between the disc and corona, we always set the albedo, i.e. $a = 0'$, to conduct the Monte Carlo simulation, which means that the irradiation photons from the corona are fully absorbed by the accretion disc, then are reprocessed as the soft photons for the inverse Compton scattering in the corona. Since the albedo $a = 0'$ is adopted, we do not have reflection component in the emergent spectra. We should keep in mind that in our model, in the gas-pressure-dominated case, the origin of soft photons for the inverse Compton scattering is dominated by the reprocessed soft photons rather than the intrinsic soft photons of the accretion disc itself. A change the value of the albedo $a'$, e.g. an increase the value of $a'$ means the soft photon luminosity caused by reprocess decreases, so the Compton luminosity decreases, meanwhile the reflection luminosity increases. In our Monte Carlo simulation, for the energy conservation, we always set that the emergent luminosity is equal to the released gravitational energy. So a change the value of the albedo $a'$ in a reasonable range will change the shape of the X-ray spectrum (relative strength of the Compton component and the reflection component), but will slightly change the X-ray luminosity. So the effects of the albedo on the emergent spectrum have only very little change to our results.

As we know, the observed high-frequency quasi-periodic oscillation (HFQPO), e.g. 150–450 Hz, are consistent with the Keplerian frequency near the ISCO of a Schwarzschild black hole with masses 15–5 $M_\odot$. Meanwhile, the observed HFQPOs do not change significantly despite the sizable change in the X-ray luminosity, suggesting the connections between the HFQPOs and the mass and spin of the black hole. If the black hole mass is well constrained, the HFQPOs can be used to measure the spin of the black hole. The observed pairs of frequencies in a 3:2 ratio suggest that the HFQPOs are probably produced by some types of resonance mechanism (e.g. Abramowicz & Kluzniak 2001). In the present disc–corona model, for simplicity, we assume the accretion disc always extending down to the ISCO of a Schwarzschild black hole, i.e. ISCO is fixed at $3R_s$. The incorporation of the effects of the spin to the disc–corona model is necessary in the future to make the model more realistic, meanwhile to match the observed HFQPOs.

Observationally, there is a positive correlation between the Eddington ratio $\lambda$ and hard X-ray index $\Gamma$ for $\lambda \gtrsim 0.01$ (Wu & Gu 2008; Qiao & Liu 2013). In the present disc–corona model, the hard X-ray photon index is $\Gamma \sim 2.1$, and does not change with the mass accretion rates. In the present paper, for simplicity, we only consider the gas-pressure-dominated case for the structure of the accretion disc, i.e. only the hard-state solution is considered (Liu et al. 2002a, 2003). As discussed in Liu et al. (2003), the gas-pressure-dominated accretion disc can exist for all the mass accretion rates. When the system is accreting at $M > 1.2 M_{\rm Edd}$, the radiation-pressure-dominated accretion disc can exist extending to $50 R_s$, which predicts a soft-state solution. When the accretion rate is at $0.3 \lesssim M \lesssim 1.2 M_{\rm Edd}$, the accreting system can be at a state between the hard state and the soft state with hard X-ray index varying with mass accretion rates.

Meanwhile, in Huang et al. (2014), the jet power is estimated according to the proposed hybrid jet model (Meier 1999, 2001), from which the radio luminosity is estimated based on the empirical relation from Cyg X-1 and GRS 1915+105 (Falcke & Biermann 1996; Heinz & Sunyaev 2003; Heinz & Grimm 2005). In the present paper, based on the internal shock scenario, we calculated the emergent spectrum of the jet, which makes our results more easy to compare with observations.

6 CONCLUSION

In this work, we investigate the radio/X-ray correlation of $L_R \propto L_X^{-1.4}$ for $L_X/L_{\rm Edd} \gtrsim 10^{-3}$ within the framework of a disc corona–jet model, in which a fraction of the matter, $\eta$, is assumed to be ejected to form the jet. We calculate the slope of the radio/X-ray correlation by assuming a constant $\eta$ for different $M$. For $\eta = 0.2$ per cent, it is found that $L_{5.5\, \rm GHz} \propto L_{1\, \rm keV}^{1.4}$ with $\xi/q \sim 1.35$. For $\eta = 0.5$ per cent, we derive that $L_{5.5\, \rm GHz} \propto L_{1\, \rm keV}^{1.7}$ with $\xi/q \sim 1.32$, which is very close to the case of $\eta = 0.2$ per cent. As an example, for different $M$, by changing the value of $\eta$, we fit the observed radio/X-ray correlation of black hole X-ray transients H1743–322 for $L_{1.9\, \rm keV}/L_{\rm Edd} > 10^{-3}$. It is found that $\eta$ is weakly dependent on $M$, and the mean fitting value of $\eta$ is $\sim 0.57$ per cent. We note an interesting result, i.e. the mean fitting result of $\eta \sim 0.57$ per cent for the radio/X-ray correlation of $L_R \propto L_X^{-1.4}$ during the high-luminosity phase is systematically less than that of the case for the low-luminosity phase (at least $\eta \gtrsim 1$ per cent), which may put some constraints on the jet formation, i.e. by suggesting that the strength of the jet power is relatively suppressed during the high-luminosity phase in BHBs.

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