A model of magnetically induced disc–corona for black hole binaries

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Abstract

We propose a model of magnetic connection (MC) of a black hole with its surrounding accretion disc based on large-scale magnetic field. The MC gives rise to transport of energy and angular momentum between the black hole and the disc, and the closed field lines pipe the hot matter evaporated from the disc, and shape it in the corona above the disc to form a magnetically induced disc–corona system, in which the corona has the same configuration as the large-scale magnetic field. We numerically solve the dynamic equations in the context of the Kerr metric, in which the large-scale magnetic field is determined by dynamo process and equipartition between magnetic pressure and gas pressure. Thus we can obtain a global solution rather than assuming the distribution of large-scale magnetic field beforehand. The main MC effects lie in three aspects. (1) The rotational energy of a fast-spinning black hole can be extracted, enhancing the dissipation in the accretion disc, (2) the closed field lines provide a natural channel for corona matter escaping from disc and finally falling into black hole and (3) the scope of the corona can be bounded by the conservation of magnetic flux. We simulate the high-energy spectra of this system by using Monte Carlo method, and find that the relative hardness of the spectra decreases as accretion rate or black hole spin increases.

We fit the typical X-ray spectra of three black hole binaries (GRO J1655−40, XTE 1118+480 and GX 339−4) in the low/hard or very high state.

Key words: accretion, accretion discs – black hole physics – magnetic fields – X-rays: binaries.

1 Introduction

It is well known that black hole binary transients present different spectra in different stages during their outbursts, which are usually referred to as low/hard state (LHS), high/soft state and intermediate (or very high) state (McClintock & Remillard 2006, hereafter MR06). It is commonly realized that how to interpret the different spectral profiles and the inducement of state transitions may be the key to look into the real physical processes during the outbursts.

Accretion disc is generally considered as the main energy source for compact objects. Historically, authors proposed various accretion models to interpret different observed spectra and light curves, such as standard thin disc (Shakura & Sunyaev 1973, hereafter SS73; Pringle 2006) and advection-dominated accretion flow (ADAF; Narayan & Yi 1994). The main criteria to define different spectral states are the relative weight of power-law component to thermal component in X-ray spectra, and the photon index of power-law component (MR06). However, we cannot expect to interpret the various observed spectra based on a single accretion mode. For example, standard thin disc is largely good for soft spectra of high/soft state, but it cannot interpret the huckneyed power-law component in high-energy spectra. ADAF is congenitally propitious to hard spectra of LHS, but it is invalid in fitting the observed soft excess and also inverse radio spectra. Recently, it is generally considered that different spectral components have different origins, i.e. the thermal component of X-ray spectra comes from the blackbody radiation of a standard thin disc, while the power-law component arises from corona or jet. Furthermore, radio emission is usually considered to be dominated by the synchronization radiation from jet.

Angular momentum transport is the essence of accretion theory. SS73 proposed the seminal alpha viscosity law to discuss complicated viscous process. Balbus & Hawley (1991) argued that magnetic rotation instability of tangled magnetic field within accretion disc would be the physical origin of viscosity, and it is generally regarded as another milestone of accretion theory. On the other hand, the heating mechanism for corona is another open question, in which magnetic field plays an essential role. The most popular sketch is that the tangled small-scale magnetic field amplified by dynamo process buoys up into corona and then reconnects, heating corona by magnetic energy dissipation. Meanwhile, the collimation mechanism of observed relativistic jets is also under controversy. Recently, Miller et al. (2008) carefully investigated the origin of disc wind of GRO J1655−40 during its outburst in 2005. Interestingly, he ruled out several popular sketches for launching disc wind and concluded that the disc wind of GRO J1655−40 must be driven

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by magnetic field. More and more attention has been paid to the important role of magnetic fields in spectral states of black hole binaries.

As is well known, the Blandford–Znajek (BZ) process is an important mechanism for jet production, in which energy is extracted efficiently from a spinning black hole to power remote astrophysical loads by invoking ‘open’ large-scale magnetic field and frame dragging effect. The BZ process can be regarded as the magnetic Penrose process (Penrose 1969; Blandford & Znajek 1977; Livio, Ogilvie & Pringle 1999). As a variation of the BZ process, closed field lines connecting a black hole with its surrounding accretion disc lead to the transfer of energy and angular momentum between the hole and the disc, and it is referred to as the magnetic connection (MC) process (Li 2002; Wang, Xiao & Lei 2002). The direction of such transport is determined by the angular velocity of the hole relative to that of the disc. Energy can be extracted efficiently from a spinning black hole with $a_\ast > 0.3594$ to the inner accretion disc in the MC process, enhancing disc radiation and a very steep emissivity index (Wilms et al. 2001; Wang et al. 2003).

However, the importance of the MC remains controversial. Tomimatsu & Takahashi (2001) obtained a global magnetospheric structure with a closed loop and open field lines threading the inner and outer parts of the disc, and the poloidal magnetic field is generated by a toroidal electric current in a thin disc with an inner edge based on the vacuum Maxwell equations in the Schwarzschild background. They found that the MC between the black hole and the disc breaks down if a uniform external field is strong enough. Hirose et al. (2004, hereafter H04) presented a detailed analysis of the magnetic field structure based on a set of three-dimensional general relativistic magnetohydrodynamic (GRMHD) numerical simulations of accreting tori in the Kerr metric with different black hole spins. Very recently, Fragile & Meier (2008, hereafter FM08) presented one of the first physically motivated two-dimensional GRMHD numerical simulations of a radiatively cooled black hole accretion disc, and they obtained a magnetically dominated accretion flow (MDAF) in the interior with an outer ADAF. It turns out that the importance of the MC depends on the radiative cooling, which is not taken into account in the non-radiative simulations of H04. As argued in FM08, a more ordered magnetic field could be formed due to the radiative cooling, by which a dramatic increase in the dominance of magnetic stresses is created. Considering the fact that a standard thin disc with a very effective radiative cooling is adopted in our model, we expect that the MC configuration of the closed magnetic field lines can be formed.

Another controversial issue involves the stresses on the inner edge of an accretion disc. Some authors (Gammie 1999; Krolik 1999; Agol & Krolik 2000) argued that the torques exerted on the inner edge of a disc might arise from the MC to the plunge region. Hawley & Krolik (2002) showed that magnetic stresses between the plunge region and the inner disc grow 10 times the value of stresses in the disc body. Garofalo & Reynolds (2005) showed the importance of such inner disc torques and how they modify the dissipation profile of a standard accretion disc even for Schwarzschild black holes. On the other hand, Paczynski (2000) and Afshordi & Paczynski (2003) suggested that the zero-torque condition is likely to be a good approximation for geometrically thin discs. This result was confirmed by Shafee, Narayan & McClintock (2008) who, using a global height-integrated model, showed that modifications to the stress profile are negligibly small for disc thickness $h$ less than about a tenth of the local radius $r$. Since only a thin disc with corona is involved in our model, we neglect the stresses on the inner edge of the accretion disc for simplicity.

Corona is a layer of hot tenuous plasma with temperature $T_c > \sim 10^7$ K above accretion disc. The soft photons emitted from disc corona are scattered up by relativistic electrons in corona, resulting in a much harder spectrum. Corona is usually invoked to interpret the power-law spectral component from tens of keV to hundreds of keV observed in black hole binaries. The main differences between various corona models lie in the heating mechanism and the configuration of corona (i.e. temperature, density and geometry). Stella &Nosner (1984) argued that tangled magnetic field amplified by dynamo process could float into corona and reconnect there, thus corona is heated by the dissipated magnetic energy. With the assumption corona geometry, Liu, Mineshige & Shibata (2002, hereafter LMS02) proposed a disc–corona system by resolving equation of energy with the balance between thermal conduction and corona evaporation. It is noted that coronas make spectra harder, but cannot augment total luminosities. In addition, Merloni & Fabian (2002, hereafter MF02) pointed out that corona is also a perfect launching site for outflow from accretion disc.

In this paper, we propose a magnetic disc–corona model, in which the magnetic field configuration is determined self-consistently, and we discuss the effects of magnetically induced corona on spectra of a relativistic thick Keplerian disc. Based on a few assumptions, we obtain a global solution of dynamic equations of accretion disc, by which the interaction of corona, the origin of large-scale magnetic field and the MC process are clarified. In this model, the MC process not only transfers rotational energy from black hole to the inner disc, but also provides a natural tube for evaporated hot plasma to fall into the hole as argued in FM08. The tenuous hot plasma is constrained and forced to move along the magnetic field lines, giving rise to corona naturally according to the configuration of the closed field lines. We assume that corona is of the same configuration as the closed magnetic field for the MC process, and calculate the boundary radius of corona based on evolving the magnetic field configuration. It turns out that the disc–corona system overwhelmingly dominates the high-energy radiation of whole system.

Both the tangled small-scale magnetic field within accretion disc and the ordered large-scale magnetic field related to the MC process are involved in this model. It is assumed that the energy density of small-scale magnetic field and the gas pressure within the disc are of the same order based on energy equipartition. Magnetic rotational instability (MRI) or turbulence of tangled small-scale magnetic field is expected to work for viscous dissipation, while extraction and transport of energy and angular momentum arise mainly from the large-scale magnetic field. The small-scale magnetic field can be amplified by dynamo process, and corona is heated by magnetic buoyancy and reconnection. Large-scale magnetic field is generated from the small-scale magnetic field, and the former is scaled by the disc radius and its intensity is usually one–three order weaker than the latter. We present a numeric code to solve the coupled dynamic equations of this magnetic disc–corona system self-consistently and simulate its spectra by using Monte Carlo method.

This paper is organized as follows. We outline the model in Section 2, where the coupled disc–corona system and the MC process are included. In Section 3, we numerically resolve the magnetic disc–corona system and simulate the high-energy spectra from the inner disc by using Monte Carlo method. In addition, four sampling results are presented with detailed analysis. In Section 4, we fit the typical X-ray spectra of three black hole binaries during their outbursts. Section 5 presents the discussion with a brief conclusion.

The Boyer–Lindquist coordinates and geometric units $G = c = 1$ are used throughout this paper.


2 MODEL DESCRIPTION

2.1 Disc and corona

In standard thin disc model, the interior viscous stress \( t_{\phi} \) is usually assumed to be proportional to total pressure \( P_{\text{tot}} \) including gas pressure, radiation pressure and magnetic pressure, namely the famous alpha viscosity law (SS73). Viscous stress is alternatively assumed to be proportional to gas pressure \( P_{\text{gas}} \), or radiation pressure \( P_{\text{rad}} \) or the geometrical mean of gas pressure and total pressure \( \sqrt{P_{\text{gas}} P_{\text{tot}}} \) and so on (Stella & Nosner 1984; Taam & Lin 1984; Wandel & Liang 1991; Wang, Watarai & Mineshige 2004, table 2 and references therein). Wang et al. (2004) fitted the X-ray luminosities of 56 radio-quiet active galactic nuclei (AGNs) and concluded that the observations prefer to the interior viscous stress proportional to gas pressure. If interior viscous process is dominated by tangled small-scale magnetic field, the viscous pressure should be comparable to magnetic pressure (Balbus & Hawley 1991; MF02), and we assume

\[-t_{\phi} = \alpha P_{\text{gas}} \sim P_{\text{mag}} = B_0^2 / 8\pi.\]  

\hspace{0.5cm} (1)

According to typical disc–corona scenario, part of the viscously dissipated energy \( Q \) is released as \( Q_{\text{corr}} \) in the disc, emitting eventually as blackbody radiation and supplying seed photons for Comptonization of corona. The rest dissipated energy, \( Q_{\text{cor}} \), heats corona and maintains its relativistic temperature via magnetic reconnection. The quantity \( Q_{\text{mag}} \) is proportional to magnetic energy density and local Alfvén speed (LMS02; MF02), and we have

\[Q = Q_{\alpha}^+ + Q_{\text{cor}}^+ = Q_{\text{corr}} / f_{\text{corr}}.\]  

\hspace{0.5cm} (2)

\[Q_{\alpha}^+ = \sigma T_{\alpha}^2, \quad Q_{\text{cor}}^+ = \frac{B_0^2}{4\pi} V_{\Lambda} = \frac{B_0^3}{4\pi \sqrt{\alpha} \rho},\]  

\hspace{0.5cm} (3)

where \( B_0 \), \( V_{\Lambda} \) and \( \rho \) are the intensity of interior tangled small-scale magnetic field, local Alfvén speed and mass density, respectively. \( T_{\alpha} \) is the effective temperature of accretion disc and \( \sigma \) is the Stefan–Boltzman constant.

In the context of relativistic hot corona, inverse Compton scattering is very effective, by which corona cooling is dominated. According to energy balance given by LMS02, \( Q_{\alpha}^+ = Q_{\text{comp}} \). We have

\[\frac{B_0^3}{4\pi \sqrt{\alpha} \rho} = \frac{4k T_{\text{corr}}}{m_e} \tau_{\text{corr}} U_{\text{corr}},\]  

\hspace{0.5cm} (4)

where \( U_{\text{corr}} = a T_{\text{corr}}^2 = 4Q_{\alpha}^+ \) is the radiative energy density at vicinity of disc surface. \( T_{\text{corr}} \) and \( \tau_{\text{corr}} \) are the temperature and the optical depth of corona. The quantities \( k, m_e \) and \( a \) are the Boltzman constant, electron mass and radiation constant, respectively. Observations reveal that optical depths of corona for AGNs and for black hole binaries in LHS lie in a very narrow range around \( \tau_{\text{corr}} \sim 1 \) (Gierlinski et al. 1997; Zdziarski 1999), and we adopt \( \tau_{\text{corr}} = 1 \) for facility, i.e.

\[\tau_{\text{corr}} = n_{e\alpha} l \sim 1,\]  

\hspace{0.5cm} (5)

where \( n_{e\alpha} \) and \( l \) are the number density of electron and the height of corona, respectively.

2.2 The MC process

Being different from standard thin disc, energy dissipation \( Q \) in this model arises from two sources: one is the gravitationally bound energy of accreting matter, and the other is the rotational energy extracted from the black hole via the MC process (Wang et al. 2002).

A fast-spinning black hole exerts a significant torque on its surrounding disc, if the two are coupled by the closed magnetic field. Energy and angular momentum are transferred between the two simultaneously. The torque exerted by the black hole on to an infinitesimal annular region of the disc is given by

\[d T_{\text{MC}} = 2 \left( \frac{d \psi}{2\pi} \right)^2 (\Omega_h - \Omega_d) = 4\pi \tau \, d r \, H_{\text{MC}},\]  

\hspace{0.5cm} (6)

where \( H_{\text{MC}} = (1/4\pi r) d T_{\text{MC}} / d r \) is the flux of angular momentum transferred from the black hole to the disc. The quantities \( \Omega_h \) and \( \Omega_d \) are the angular velocity of the black hole and that of the disc, respectively. The quantity \( \psi = \psi(r, \theta) \) is the magnetic flux through a surface bounded by a curve with \( r = \) constant and \( \theta = \) constant, and we have

\[d \psi = B_\theta \, 2\pi r \, d r \, |_{\theta=\pi/2} = -B_h \, 2\pi r_h \, 2M \sin \theta \, d \theta \, |_{\theta=\pi/2}.\]  

\hspace{0.5cm} (7)

\( r_h \) is the radius of black hole horizon and the resistance of the horizon corresponding to the magnetic flux is written as (Wang et al. 2002)

\[d Z_h = \left( \frac{R_h}{2} \right) \frac{r_h^2 + M^2 a^2 \cos^2 \theta}{(r_h^2 + M^2 a^2 \sin^2 \theta)} \, d \theta \, \frac{d \theta}{d r},\]  

\hspace{0.5cm} (8)

where \( R_h \) is the surface resistivity of black hole horizon. \( M \) and \( a \) are the mass and the dimensionless spin of black hole, respectively.

In equation (7), \( B_\theta \) is the poloidal component of the large-scale magnetic field anchored on the disc. Equation (7) is derived from conservation of magnetic flux, by which the mapping relation \( r(\theta) \) between black hole horizon and the inner region of the disc can be determined. Assuming that the inner edge of the disc connects the horizon at \( \theta = \pi/2 \), we obtain the outer boundary of the MC region, \( r(\theta) = 0 \), by integrating equation (7) from \( \theta = \pi/2 \) to 0.

Still, we have to estimate magnetic field strength on the horizon required by equations (6) and (7). Assuming a uniform magnetic field on the horizon and adopting the equilibrium between magnetic pressure and the ram pressure given by Moderski, Sikora & Lasota (1997), we have

\[B_h = \sqrt{2M_d / r_h^2},\]  

\hspace{0.5cm} (9)

where \( M_d \) is accretion rate.

The relativistic conservation equations of energy and angular momentum for a disc with MC can be written as (Li 2002)

\[
\frac{d}{d r} \left( M_d L^I - g \right) = 4\pi r \left( Q L^I - H_{\text{MC}} \right),
\]  

\hspace{0.5cm} (10)

\[
\frac{d}{d r} \left( M_d E^I - \Omega_d \right) = 4\pi r \left( Q E^I - H_{\text{MC}} \Omega_d \right).\]  

\hspace{0.5cm} (11)

The quantities \( Q \) and \( g \) are the dissipated energy per unit disc surface and interior viscous torque of the disc, respectively. \( E^I \) and \( \Omega_d \) are, respectively, the specific energy, specific angular momentum and angular velocity of the test particles in the equatorial plane of a Kerr black hole (Bardeen, Press & Teukolsky 1972):

\[
\Omega_d = \sqrt{M/r^3 / (1 + a^2 / r^2)},
\]

\[
E^I = \frac{(1 - 2/r + a^2/r^2)}{\sqrt{1 - 3/r^2 + 2a^2/r^3}^2}, \quad L^I = \sqrt{Mr^2 / (1 - 3/r^2 + 2a^2/r^3)^{3/2}}.
\]  

\hspace{0.5cm} (12)

where \( r \) is \( r / M \). The quantities \( A \) and \( D \) in equation (7) are relativistic correction factors in Kerr metric, and they read

\[A = 1 + a^2 / r^2 + 2a^2 / r^3, \quad D = 1 - 2 / r + a^2 / r^2.\]  

\hspace{0.5cm} (13)
We can derive the energy dissipation $Q$ and interior viscous torque $g$ by resolving equations (10) and (11):

$$Q(r) = Q_{DA} + Q_{MC} = Q_{DA} + \frac{1}{r} \int_{r_{\text{in}}}^{r} \frac{d\Omega_{D}}{d\Omega} (E^{\uparrow} - \Omega_{D} L^{\uparrow}) H_{MC} r dr,$$

$$Q_{DA} = \frac{1}{4\pi r} \int_{r_{\text{in}}}^{r} \frac{d\Omega_{D}}{d\Omega} (E^{\uparrow} - \Omega_{D} L^{\uparrow}) M_{D} dL,$$

$$g(r) = \frac{E^{\uparrow} - \Omega_{D} L^{\uparrow}}{-d\Omega_{D}/dr} Q(r),$$

where $r_{\text{in}}$ is the radius of the innermost stable circular orbit (ISCO), which is assumed to be the inner edge of accretion disc.

In this model we intend to resolve the dynamic equations combining the MC effects, which might change the dynamic property of accretion disc significantly. To resolve equations (14)–(16), we adopt the relation between the large-scale magnetic field above the disc and tangled small-scale magnetic field in the disc as follows (Livio et al. 1999):

$$B_{p} \sim \left(\frac{\hat{h}}{r}\right) B_{D},$$

where $\hat{h}$ is the half height of the disc. The intensity and distribution of $B_{D}$ and $B_{p}$ can be derived by resolving the dynamic equations.

### 3 NUMERICAL RESULTS

For facility, we consider a slab corona with $l \sim 10r_{\text{in}}$. Inspecting equations (6)–(16) we find that MC at radius $r$ could affect the disc region beyond $r$. We design an iterative algorithm and integrate equations (10)–(16) from the ISCO to the outer boundary of the MC region, and obtain self-consistently global solutions of the disc–corona system, in which the full solutions of corona and the MC effects are included. As argued above, energy can be extracted from a fast-spinning black hole via the MC process, resulting in the enhancement of dissipation in the disc. Subsequently, the disc height, pressure and magnetic field increase. It is noted that the MC effects scaled by the square of magnetic field become very strong for the amplified magnetic field. Since corona heating via magnetic reconnection is scaled by the cube of magnetic field (cf. equation 3), we expect that a stable saturated magnetic configuration can be maintained in our model.

The iterative algorithm consists of the following steps: (1) resolving numerically the disc–corona system without the MC process; (2) deriving the large-scale magnetic field and calculating the energy extraction by the MC process; (3) combining the energy dissipation of the disc with the MC process, and resolving the disc–corona system; (4) repeating steps (2) and (3) until the magnetic field is saturated; (5) integrating outward to a larger radius ($r \sim r + dr$); (6) repeating (1)–(5) until the outer boundary of MC process [$\theta(r) = 0$] is reached.

Here we present four typical solutions as shown in Figs 1–2, 3–4, 5–6 and 7–8, where $T_{D}$ is the temperature of accretion disc on the equatorial plane. The concerned parameters are listed in Table 1, in which the black hole mass $m_{bh}=\dot{M}/M(C)$, distance $D$, inclination angle $i$, corona height $l$, viscous coefficient $\alpha$, black hole spin $a_{\ast}$, and accretion rate $\dot{m}$ (in unit of the Eddington rate) are included. The first three parameters are constrained by observations. The viscous coefficient is taken as a typical value, $\alpha = 0.3$. In fact the corona height might vary with the disc radius, and its value could influence the density of corona. Fortunately, emerged spectrum from corona is mainly determined by the temperature and optical depth. Since we

![Figure 1](https://academic.oup.com/mnras/article-abstract/394/4/2310/1208615/2310?wrap=1)

*Figure 1.* A global solution of the magnetic disc–corona system in the cases of large accretion rate and large black hole spin (sample 1). Quantities are plotted in dashed and solid lines for disc + corona and disc + corona + MC, respectively.
**Figure 2.** Emerged spectrum from the disc–corona system in the case of large accretion rate and large black hole spin (sample 1). The total emissive spectrum and its thermal, Comptonized and reflective components are plotted in thick–zigzag, solid, dashed and thin–zigzag lines, respectively.

**Figure 3.** A global solution of the magnetic disc–corona system in the cases of small accretion rate and small black hole spin (sample 2). Quantities are plotted in dashed and solid lines for disc + corona and disc + corona + MC, respectively. (The dashed and solid lines almost coincide completely.)
Figure 4. Emerged spectrum from the disc–corona system in the cases of small accretion rate and small black hole spin (sample 2). The total emissive spectrum and its thermal, Comptonized and reflective components are plotted in thick–zigzag, solid, dashed and thin–zigzag lines, respectively.

Figure 5. A global solution of the magnetic disc–corona system in the cases of large accretion rate and small black hole spin (sample 3). Quantities are plotted in dashed and solid lines for disc + corona and disc + corona + MC, respectively. (The dashed and solid lines almost coincide completely.)

adopt a constant optical depth for corona, our results are not sensitive to \( l \), and we fix \( l = 10r_{\text{ms}} \) in calculations. So there are actually only two free parameters in our model, accretion rate \( \dot{m} \) and black hole spin \( a_* \). The former represents the ‘fuel supply’, and the latter determines the radiant efficiency (luminosity per unit mass). Both parameters are very important for the emerged spectrum. Actually, we can demonstrate that they are the key elements of the spectral profile.
3.1 The MC effects on accretion disc

The MC process utilizes the differential rotation between a black hole and its accretion disc to transfer energy and angular momentum. As argued by Wang et al. (2002), the MC effects become much stronger for greater black hole spin. In this paper, we find that the MC effects on accretion disc also depend on accretion rate. The distribution of closed field lines and corona is very concentrated to
the innermost region of accretion disc ($<\sim 20M$) for great accretion rate ($>\sim 0.2M_{\text{Edd}}$). Thus the energy pumped into the disc via the MC process is comparable to the released gravitational energy and the radiation efficiency of the system is enhanced significantly. As shown in Figs 1(a) and (e), both temperature and dissipation rate of the disc are augmented obviously due to the MC effects. It is interesting to note that the MC process has little influence on gas pressure, but it strengthens radiation pressure significantly. As a result, the inner region of disc becomes thick enough, being apt to form large-scale magnetic field. On the other hand, the stronger is the large-scale magnetic field, the more efficient is the MC process. So the energy dissipation and the MC process promote each other in our model. When accretion rate is small ($<\sim 0.05M_{\text{Edd}}$), the distribution of closed field lines and corona can extend to $>\sim 100M$. In this case, the magnetic field is too weak to give rise to obvious effects on the disc dynamics, and the closed field lines mainly provide a channel for corona matter escaping from the disc and finally falling into the hole.

Recalling our previous researches, we conclude that transport of energy and angular momentum via the MC process is generally concentrated in a very narrow region ($\sim 10M$) near the inner disc boundary. However, it can change the total luminosity of the whole system significantly.

3.2 Emerged spectra of the disc–corona system

We find that spectral profiles change obviously with both accretion rate and black hole spin. Generally, thermal radiation mainly comes from the disc, and power-law component comes from corona, implying that the higher corona temperature has the harder spectrum.

(1) The fraction of thermal component increases as accretion rate increases. When accretion rate increases, the magnetic field and thermal production are enhanced, resulting in much more soft photons escaping from the surface of disc. Thus the corona temperature is suppressed effectively by the cooling of Comptonization.

(2) The fraction of power-law component decreases as black hole spin increases. The gravitational potential well becomes very deep as the black hole spins fast. On the other hand, the stronger frame dragging effects give rise to more energy transferred from a spinning
hole to the disc in the MC process. Both effects can strengthen the radiation from the inner disc as well as suppress the corona temperature.

Generally speaking, the total luminosity of the disc–corona system is positively correlated to accretion rate and black hole spin. We find that the spectra are always dominated by thermal component when accretion rate or black hole spin is large (e.g. \( \dot{M}_D > 0.3 \dot{M}_{\text{Edd}} \), \( a_* > 0.9 \)), and these results are in agreement with those obtained by Esin, McClintock & Narayan (1997).

4 COMPARISON TO OBSERVATIONS

We try to fit the typical X-ray spectra of three black hole binaries in the LHS or very high state, i.e. GRO J1655−40, XTE 1118+480 and GX 339−4. The data are taken from the literature (without error bars): GRO J1655−40 (Brocksopp et al. 2006), XTE 1118+480 (Yuan, Cui & Narayan 2005 and references therein), GX 339−4 (Miller et al. 2004).

As shown in Figs 9 and 10, the hard X-ray spectra with low luminosity (GRO J1655−40 and XTE 1118+480 in LHS) are well fitted. In these simulations, the accretion rates are small, gravitational binding energy is mildly released along the inner region of accretion disc and most of the energy (larger than 80 per cent) is dissipated in corona via magnetic reconnection (cf. Fig. 3f). It turns out that the spectra are hard but dim. Inspecting Fig. 11, we find that the soft X-ray spectrum with very high luminosity of GX 339−4 in very high state can also be well fitted. In this simulation, the accretion rate and black hole spin are large. Gravitational binding energy is released efficiently and efficacy of MC process also becomes significant. Energy dissipation is concentrated at the inner most region of the disc. Meanwhile, there is only a small fraction of dissipated energy distributed to corona (cf. Fig. 1f). It turns out that the spectrum is soft but bright.

However, there are excesses in soft X-ray band in these simulations, when we try to fit the total X-ray spectra. Since it is an embryo model, we cannot expect our model to fit the full features of the spectra.

5 DISCUSSION

In this paper, we propose a magnetic disc–corona model, in which the configuration of large-scale magnetic field and corona can be self-consistently determined with several minimal assumptions. We combine accretion disc, corona, origin of large-scale magnetic field and the MC process into this model to investigate the interaction among them. The global solutions are obtained numerically. The size of corona can be self-consistently determined by resolving the magnetic configuration of the MC process. It is found that the MC process could change the properties of accretion disc significantly for a large accretion rate. In addition, we simulate the emerged spectra from the inner region of accretion disc by using Monte Carlo method.

Observations reveal that large-scale magnetic fields exist in compact objects. However, the origin of large-scale magnetic field is still under controversy. The popular treatment of large-scale magnetic field is invoked magnetohydrodynamical (MHD) simulations. It is particularly noted that Uzdensky (2004, 2005) investigated the MC between a black hole and its surrounding disc, and he solved the Grad–Shafranov equations to determine the configuration of large-scale magnetic field in a force-free magnetosphere. Instead, we use the phenomenal description of dynamo mechanism to avoid
complex calculations, and treat the origin of large-scale magnetic field directly by invoking the dynamics of accretion disc. In our model, the large-scale magnetic field, corona and accretion disc are connected very closely, which cannot be separated from each other.

It turns out that in this model the emerged spectra change significantly with accretion rate, naturally giving rise to hard spectra with low luminosity and soft spectra with high luminosity. This feature might be related to the state transitions of black hole binaries.

Figure 10. XTE J1118+480 in LHS. The concerned parameters are listed in Table 1. The embedded small figure is the emerged spectrum of our model. It is shown that the X-ray spectrum ($> \sim 0.1$ keV) can be fitted in the rough. The excess in lower energy band below 0.1 keV might arise from bolometric radiation from the outer disc region and synchrotron radiation of jet, which is beyond the scope of this paper (cf. Yuan et al. 2005).

Figure 11. GX 339−4 in very high state (2002.09.29). The concerned parameters are listed in Table 1. The embedded small figure is the emerged spectrum of our model. It is shown that the hard X-ray spectrum ($> \sim 2$ keV) can be well fitted. It is expected that the excess in soft X-ray band could be absorbed by the surrounding medium (cf. Miller et al. 2004).
The BP process is a very important mechanism for disc wind and jet production, which is also related directly to large-scale magnetic field. In the BP process, accreting matter could be thrown centrifugally off accretion disc and accelerated along the field lines. The outflow can be self-collimated to jet due to magnetic pinch effect. However, it would become disc wind for weak magnetic field. The BP process can change the accretion rate of the inner disc region likely and thus affect the high-energy emission of the system. It might play a very important role in state transitions of black hole binaries. The outflow is also expected to produce some radiation and absorptive effects. Although there is little evidence of BP winds in GRMHD (see e.g. H04), the observed rich absorptive lines of GRO J1655−40 are likely related to winds driven by the BP process (Miller et al. 2008). The presence of BP process in our model would help to fit the observations and we leave it to the future work.

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