REVISITING THE STRUCTURE AND SPECTRUM OF THE MAGNETIC-RECONNECTION-HEATED CORONA IN LUMINOUS AGNs

J. Y. Liu 1,2, E. L. Qiao 3, and B. F. Liu 3

1 National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; jly0807@ynao.ac.cn
2 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China
3 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; qiaoe@nao.cas.cn, bliu@nao.cas.cn

Received 2016 February 23; revised 2016 September 19; accepted 2016 October 9; published 2016 December 6

ABSTRACT

It is believed that the hard X-ray emission in the luminous active galactic nuclei (AGNs) is from the hot corona above the cool accretion disk. However, the formation of the corona is still debated. Liu et al. investigated the spectrum of the corona heated by the reconnection of the magnetic field generated by dynamo action in the thin disk and emerging into the corona as a result of buoyancy instability. In the present paper, we improve this model to interpret the observed relation of the hard X-ray spectrum becoming softer at higher accretion rate in luminous AGNs. The magnetic field is characterized by $\beta_0$, i.e., the ratio of the sum of gas pressure and radiation pressure to the magnetic pressure in the disk ($\beta_0 = (P_{g,d} + P_{r,d})/B_0$). Besides, both the intrinsic disk photons and reprocessed photons by the disk are included as the seed photons for inverse Compton scattering. These improvements are crucial for investigating the effect of magnetic field on the accretion disk corona when it is not clear whether the radiation pressure or gas pressure dominates in the thin disk. We change the value of $\beta_0$ in order to constrain the magnetic field in the accretion disk in luminous AGNs. We find that the energy fraction released in the corona ($f$) gradually increases with the decrease of $\beta_0$ for the same accretion rate. When $\beta_0$ decreases to less than 50, the structure and spectrum of the disk corona are independent of accretion rate, which is similar to the hard spectrum found in Liu et al. Comparing with the observational results of the hard X-ray bolometric correction factor in a sample of luminous AGNs, we suggest that the value of $\beta_0$ is about 100–200 for $\alpha = 0.3$, and the energy fraction $f$ should be larger than 30% for hard X-ray emission.

Key words: accretion, accretion disks – galaxies: active – X-rays: galaxies

1. INTRODUCTION

An active galactic nucleus (AGN) is a very compact region located at the center of a galaxy, which can emit from radio to X-rays. The radiation from AGNs is believed to be powered by accreting the surrounding matter onto the supermassive black hole. Observations indicate that different types of AGNs may have different accretion modes. For the low-luminosity AGNs (LLAGNs), roughly $L_{\text{bol}} < 10^{44}$ erg s$^{-1}$, due to the low radiative efficiency, the radiation is generally believed to be dominated by a faint, radiatively inefficient accretion flow (RIAF; e.g., Narayan & Yi 1994, 1995a, 1995b; Quataert et al. 1999; Ho 2008; Yuan & Narayan 2014). The case of luminous AGNs, mainly including quasars and bright Seyfert galaxies, is different. The spectral energy distribution (SED) of luminous AGNs can be characterized by different components: a “big blue bump” in optical-to-ultraviolet (UV) band, which is often explained by a geometrically thin, optically thick accretion disk extending down to the innermost stable circular orbits (ISCO; Shakura & Sunyaev 1973; Shields 1978; Malkan & Sargent 1982; Elvis et al. 1994; Kishimoto et al. 2005; Shang et al. 2005); a soft X-ray excess, whose origin is still unclear (Done et al. 2007); and a power-law hard X-ray emission, which is believed to be produced by the inverse Compton scattering of the soft photons from the accretion disk in a hot corona above (e.g., Svensson & Zdziarski 1994; Magdziarz et al. 1998; Chiang 2002; Vasudevan & Fabian 2009). In luminous AGNs, the hard X-ray spectrum is often described by a power law with $\Gamma_{2-10\text{ keV}} \sim 1.9$. Meanwhile, it is found that there is a positive correlation between $\Gamma_{2-10\text{ keV}}$ and $L_{\text{edd}}$ ($\lambda_{\text{edd}} = 2\times 10^{28}(M_{\bullet}/M_\odot)$ erg s$^{-1}$), whereas a negative correlation is found between $\Gamma_{2-10\text{ keV}}$ and $L_{\text{edd}}$ in LLAGNs (Gu & Cao 2009; Yang et al. 2015). In luminous AGNs, the hard X-ray luminosity is also used to estimate the bolometric luminosity with the hard X-ray bolometric correction factor $L_{\text{bol}}/L_{2-10\text{ keV}} \approx 20–150$ for $\lambda_{\text{edd}} > 0.1$ (Wang et al. 2004; Vasudevan & Fabian 2007, 2009; Zhou & Zhao 2010; Fanali et al. 2013).

The formation of coronas in AGNs is still unclear. Previous works have revealed that a corona can be fed by the evaporation of matter from an underlying cool disk (e.g., Meyer & Meyer-Hofmeister 1994; Meyer et al. 2000; Różańska & Czerny 2000a, 2000b; Liu et al. 2002a; Qian et al. 2007; Qiao & Liu 2009). In the framework of the disk evaporation model we mentioned above, if the mass accretion rate transferred from the outermost region of the disk is less than a predictive critical mass accretion rate $M_{\text{crit}} \sim 0.2 M_{\text{edd}}$, the disk will be truncated at a radius from the black hole. However, if the mass accretion rate transferred from the outermost region of the disk is greater than $M_{\text{crit}}$, the disk cannot be completely evaporated into the corona and extends down to the ISCO of the black hole. In this model, generally, the corona is presumed to be heated by the viscous heating of the corona itself. Meyer-Hofmeister et al. (2012) studied the strength of the corona for strong mass flow in the disk and found that the strong Compton cooling of the corona by the soft photons from the disk makes the corona quickly condense onto the disk. For a typical mass accretion rate of 0.1 $M_{\text{edd}}$ transferred from the outermost region of the disk, the accretion rate in the corona fed by disk evaporation is very low, i.e., less than 0.001 $M_{\text{edd}}$, which is inconsistent with the observed strong X-ray emission in most of the luminous AGNs.
In order to resolve the energy-deficiency problem, Liu et al. (2012) set the ratio \( f \) of the corona heating to the total gravitational energy to be a free parameter and found that a relatively large value of \( f \) is needed for luminous AGNs. The more energy is released in the corona, i.e., the larger \( f \), the harder the X-ray emits from the corona. For the corona heating, one of the possible mechanisms might be magnetic reconnection. The magnetic field is generated by dynamo action in the accretion disk. Due to the buoyancy instability, the magnetic flux loop emerges from the disk and reconnects with other loops in the corona, thereby releasing the magnetic energy to heat the coronal plasma. The energy is then radiated away through inverse Compton scattering (see as Tout & Pringle 1992; Di Matteo 1998; Miller & Stone 2000; Merloni & Fabian 2001; Liu et al. 2002b, 2003; Wang et al. 2004; Rózanńska & Czerny 2005; Cao 2009; Qiao & Liu 2009; Liu et al. 2012; You et al. 2012; Huang et al. 2014). Liu et al. (2002b, 2003) constructed a disk-corona model with the corona heated by the magnetic reconnection and calculated the corresponding emergent spectra. The magnetic field strength is characterized by a parameter \( \beta \sim 1 \) (with \( \beta = P_d/P_b \), i.e., the ratio of gas pressure to magnetic pressure at the midplane of the disk). In their work, the disk is divided into two types, i.e., the gas-pressure-dominated case and radiation-pressure-dominated case. They found two types of solutions corresponding to hard spectrum and soft spectrum. For the hard-spectrum solution, the energy fraction \( f \) is nearly 1, and the hard X-ray spectrum index with \( \alpha \sim 1.1 \) \( (f \propto \nu^{-\alpha}) \) does not change with mass accretion rate. In the soft-spectrum solution, the energy fraction \( f \) is nearly 0, implying that the X-ray emission is also nearly 0. These two solutions only correspond to the two end points in the observed relation of the hard X-ray spectrum becoming softer at higher accretion rate in luminous AGNs. Even though there are composed solutions for moderate luminosity, e.g., \( M = 0.5 M_{\odot} \) shown in the right panel of Figure 1 in Liu et al. (2003), the thin disk abruptly changes from being radiation pressure dominated to being gas pressure dominated at a radius, and the energy fraction also directly increases to 1 from 0. The distribution of the parameters in the corona, such as electron temperature, density, and the optical depth, is not continuous. However, the observed hard X-ray spectrum is softer at higher accretion rate, which means that the energy fraction smoothly decreases with the accretion rate. Obviously, the previous model cannot smoothly reproduce the observed fraction of the X-ray luminosity to the bolometric luminosity.

In the present work, in order to obtain a more self-consistent solution, we improve the model in Liu et al. (2002b, 2003) and investigate the effect of magnetic field on the structure and spectrum of such a disk-corona model. The disk is not divided into two types, and the magnetic pressure is assumed to be proportional to the sum of gas pressure and radiation pressure as characterized by magnetic parameter \( \beta_0 = (P_d + P_a)/P_b \). Besides, both the intrinsic disk radiation and the backward corona Compton emission are always included for the corona Compton cooling. These improvements will help us to investigate the properties of the accretion flows when it is not clear whether the radiation pressure or gas pressure dominates in the disk. These are crucial for smoothly changing the energy fraction from 0 to 1 and predicting the observed hard X-ray emission in luminous AGNs. In order to constrain the magnetic field for a certain viscous coefficient \( \alpha \), we calculate the emergent spectrum of the model for different \( \beta_0 \) and compare the derived relation between hard X-ray bolometric correction and accretion rate with the observed relation in a sample of luminous AGNs. We suggest that the spectrum of the model with \( \beta_0 \sim 100–200 \) for viscous coefficient \( \alpha = 0.3 \) is consistent with the observed result.

The structure of the paper is as follows: The model is presented in Section 2. The numerical results for the structure and the emergent spectrum of the model are in Section 3. The discussion and the conclusion are in Sections 4 and 5, respectively.

2. THE MODEL

We adopt a geometrically thin and optically thick disk (Shakura & Sunyaev 1973). The gravitational power dissipated in an accretion disk through a viscous process per unit surface area is

\[
Q_{\text{vis}}^+ = \frac{3\mathcal{G}M_{\text{BH}} M}{8\pi R^3} \left[ 1 - \left( \frac{3R_s}{R} \right)^{1/2} \right],
\]

where \( R_s = 2GM_{\text{BH}}/c^2 \) is the Schwarzschild radius.

The equation of state of the accretion disk is

\[
P_{a,d} = P_{g,d} + P_d + P_b = (P_{g,d} + P_{a,d})(1 + 1/\beta_0)
= \left( \frac{\rho_k k T_a}{\mu m_p} + \frac{1}{3} \alpha T_d^4 \right) (1 + 1/\beta_0),
\]

where magnetic pressure \( P_b = B^2/8\pi \) is characterized by the magnetic parameter \( \beta_0 \), i.e., the ratio of the sum of gas pressure and radiation pressure to magnetic pressure.

We assume that the magnetic field is continually generated in the disk by dynamo action. Because of the buoyancy instability, the magnetic flux loops can emerge into the corona and reconnect with other loops. In this process, a fraction \( f \) of the gravitational energy stored in the magnetic field is transferred into the corona, i.e.,

\[
Q_c^+ = \frac{B^2}{4\pi} V_\lambda = f Q_{\text{vis}}^+,
\]

where Alfvén speed \( V_\lambda = \sqrt{2P_b/\mu m_p n_e} \) and \( n_e \) is the number density of electrons in the corona. Here, we take the mean molecular weight \( \mu \) to be 0.5, which is the chemical composition of pure hydrogen.

As shown in former works, the energy equilibrium of the disk is determined by the accretion energy released in the disk and irradiation by the corona (Haardt & Maraschi 1991, 1993; Cao 2009). In our present work, it is assumed that some parts of the seed photons from the disk are upward scattered as the emergent spectrum, and parts of them are scattered backward. The backward photons are reprocessed in the disk surface layer and emitted as blackbody. This means that the irradiation by the corona can only affect the disk blackbody temperature rather than the internal structure of the disk (Tuchman et al. 1990; Liu et al. 2003). Thus, the energy equation for the cold disk is

\[
Q_{\text{in}}^+(1-f) = \frac{8\sigma T_d^4}{3\tau},
\]

where \( \tau = 2.0 \rho_b H_b \kappa \) is the optical depth in the vertical direction of the disk. The height of the disk is
$H_d = c_s / \Omega = \sqrt{\frac{P_{ad}}{\rho_d} / \Omega}$. The opacity $\kappa$ is contributed by the scattering opacity $\kappa_s$ and free-free opacity $\kappa_{ff}$. We take $\kappa_s = 0.4 \text{ cm}^2 \text{ g}^{-1}$ for the chemical composition of pure hydrogen and $\kappa_{ff} = 6.4 \times 10^{22} \rho_d T_d^{-7/2} \text{ cm}^2 \text{ g}^{-1}$.

A fraction $(f)$ of angular momentum is carried into the corona along the magnetic loops, and the remaining fraction $(1 - f)$ of it is maintained in the disk, which is shown in the following equation:

$$M \Omega \left[ 1 - \left( \frac{3R_n}{R} \right)^{1/2} \right] (1 - f) = 4\pi H_d \tau_{\nu},$$

(5)

where $\tau_{\nu} = \alpha \rho_d$ is the viscosity stress.

The energy transferred from the disk is released in the corona and eventually radiated away mainly via inverse Compton scattering. The density of the corona is determined by the energy balance between the downward thermal conduction and the mass evaporation in the chromospheric layer. So the energy equations for the corona can be summarized as

$$\frac{B^2}{4\pi} V_A \approx \frac{4kT_e}{m_e c^2} \tau^s c U_{\text{rad}},$$

(6)

$$\frac{k_\nu T_\nu^2}{\ell_c} \approx \frac{\gamma}{\gamma - 1} n_e kT_e \left( \frac{kT_e}{\mu m_H} \right)^2.$$  

(7)

In Equation (6), the energy density of soft photons is $U_{\text{rad}} = \frac{1}{2} Q_{\nu} \rho_d (1 - f) + 0.4 \lambda_n \frac{B^2}{\ell_s}$, which includes both the intrinsic disk radiation and the reprocessed radiation of backward Compton emission (with albedo always being assumed to be zero in our calculations). In Equation (6), $\tau^s \equiv \sum_{\ell} \tau = \lambda_n n_e \sigma_T \ell_c$ is the effective optical depth, with an initial value of $\lambda_n = 1$. In our model, we also set $\ell_c = 10R_d$, as done in previous works (e.g., Liu et al. 2002b, 2003; Qiao & Liu 2015), since it is found that the emergent spectrum is weakly dependent on $\ell_c$.

Given the values of black hole mass $M_{\text{BH}}$, radius $R$, mass accretion rate $\dot{m}$, viscous coefficient $\alpha$, magnetic parameter $\beta_0$, and initial parameters $\lambda_n = 1.0$ and $\lambda_0 = 1.0$, we solve Equations (1)–(7) numerically and obtain the radially dependent disk temperature $T_d$, disk density $\rho_d$, temperature $T_c$, and number density of electrons $n_e$ in the corona.

With the parameters of the structure of the disk corona, we derive the spectrum of the model through Monte Carlo simulation. This method is essentially the same as that described by Pozdniakov et al. (1997), and the process was shown in detail in Liu et al. (2003). In our calculation, we consider both the intrinsic disk photons and reprocessed photons by the disk as the seed photons to be scattered in the corona. In order to get a self-consistent solution, we need to check whether the upward luminosity from the corona $L_{up}$ is approximately equal to $L_G$ (here $L_G$ is the liberated rate of total gravitational energy), and the ratio of the downward luminosity to the soft luminosity $L_{\text{down}} / L_{\text{soft}}$ is approximately equal to $\lambda^s_p$ (here $\lambda^s_p$ is the ratio of the energy of reprocessed photons to the total soft photon energy in the structure calculation). If yes, we find the right $\lambda_n$ and $\lambda_0$ for the consistent corona structure. If no, we set new $\lambda_n = 1 + \lambda_{\text{new},n} / \lambda_{\text{old},n}$ and then repeat the structure calculation and Monte Carlo simulation until the consistent conditions $L_{up} \approx L_G$ and $L_{\text{down},n} / L_{\text{soft},n} \approx \lambda^s_p$ are fulfilled.

3. RESULTS

3.1. Structure of the Disk and Corona

Given the black hole mass $M_{\text{BH}} = 10^8 M_\odot$ and viscous coefficient $\alpha = 0.3$ (as in, e.g., King et al. 2013), we numerically solve Equations (1)–(7) to obtain the radial structure of the disk corona. Since we aim to investigate the X-ray spectrum properties of luminous AGNs, the accretion rate $\dot{m} \geq 0.03$ in this work.

Numerical calculation shows that the radial structure of the disk is sensitively affected by the magnetic field. We show the radial distribution of the ratio of gas pressure to radiation pressure $(P_{g,d} / P_{d})$ in the disk for various $\beta_0$ and two values of accretion rate $\dot{m} = 0.05$ (upper panel) and 0.1 (lower panel). Solid line: $\beta_0 = 1000$; dotted line: $\beta_0 = 200$; dashed lines: $\beta_0 = 100$; dotted-dashed line: $\beta_0 = 50$; triple-dotted-dashed line: $\beta_0 = 10$. The long-dashed line denotes that $P_{g,d} / P_{d} = 1.0$.

In order to investigate the features of the corona under the effect of magnetic reconnection heating, we show the radial distribution of the energy fraction $f$, electron temperature $T_e / 10^5$, effective optical depth $\tau^s$, and effective Compton parameter $(\gamma^s = 4kT_e / m_e c^2)$ in the corona with various $\beta_0$ for $\dot{m} = 0.05$ and $\dot{m} = 0.1$, respectively, in Figure 2. For $\dot{m} = 0.05$, the energy fraction $f$ is dramatically increased from about 0.2 to 0.9 as $\beta_0$ decreases from 1000 to 200. Similar changes can be found for $\dot{m} = 0.1$ in the lower panel of Figure 1.
Figure 2. Radial distribution of parameters in the corona with different $\beta_0$ (red lines: 1000; blue lines: 200) for $m = 0.05$ (upper) and $m = 0.1$ (lower). All the parameters increase with a decrease of $\beta_0$, which means that the corona becomes stronger for larger magnetic field strength.

Figure 3. Averaged energy fraction $\tilde{T}$ (upper panel) and averaged effective Compton $y$-parameter $\bar{y}$ (lower panel) vs. accretion rate for different $\beta_0$. The denotations of different line styles are the same as those in Figure 1. Both of these two parameters decrease with the increase of accretion rate for $\beta_0 > 100$ and are the same for all accretion rates for $\beta_0 = 50$ (10).

3.2. Spectrum from the Disk and Corona

With the radial structure, the spectrum of the disk corona can be derived by Monte Carlo simulation. We plot the spectrum with different $\beta_0$ (200, 100, 50) for three different accretion rates $\dot{m}$ (0.05, 0.1, 0.5) in Figure 4. For a magnetic field with $\beta_0 = 200$, the hard X-ray is weaker for higher accretion rates. This shows that the spectrum of $\dot{m} = 0.5$ is mainly contributed by the blackbody radiation from the accretion disk. When $\beta_0 = 100$, both the spectra of $\dot{m} = 0.05$ and $\dot{m} = 0.1$ are slightly harder than that of $\beta_0 = 200$, and they seem similar, whereas the hard X-ray spectrum of $\dot{m} = 0.5$ dramatically becomes harder than that in the case of $\beta_0 = 200$. As $\beta_0$ decreases to 50, the X-ray spectra for these three accretion rates are similar, as shown in the upper panel of Figure 4. As we mentioned in the previous section, the averaged effective Compton $y$-parameter $\bar{y}$ is independent of the accretion rate when $\beta_0 = 50$, which leads to the hard X-ray spectrum hardly changing with the accretion rate. The spectrum is similar to the hard spectrum shown in Figure 5 in Liu et al. (2003).

3.3. Application in Luminous AGNs

In luminous AGNs, the observational results show that both $\Gamma_{2-10\text{ keV}}$ and $L_{\text{bol}}/L_x$ increase with accretion rate. For comparison, we plot the relation between $\Gamma_{2-10\text{ keV}}$ (and $L_{\text{bol}}/L_x$) and accretion rate for different $\beta_0$ in Figure 5. For $\beta_0 = 200$, $\Gamma_{2-10\text{ keV}}$ is about 2.2 at accretion rate $\dot{m} = 0.03$ and increases to about 3.5 at $\dot{m} = 0.5$. Correspondingly, $L_{\text{bol}}/L_x$ increases from 19 to larger than 10^4, with the accretion rate increasing from 0.03 to 0.5. When $\beta_0 = 100$, $\Gamma_{2-10\text{ keV}}$ is about...
2.17 at \( \dot{m} < 0.1 \), and it also increases to 2.8 at \( \dot{m} = 0.5 \). However, for a larger magnetic field (shown by lines with \( \beta_0 = 50, 10 \)), \( \Gamma_{2-10\text{ keV}} \) is about 2.17 for all accretion rates, which is consistent with the results in previous works (Liu et al. 2003; Cao 2009; Kawabata & Mineshige 2010). Correspondingly, \( L_{\text{bol}}/L_x \) is also constant at about 16.

In order to compare with the observed results in luminous AGNs, in the lower panel of Figure 5, the observational data (represented by big red crosses) are also plotted. These data are selected from Vasudevan & Fabian (2009), which are the binned observational data with radio-loud objects and low X-ray flux objects removed. Drawn from the plot, for \( \beta_0 = 200 \), the model fits the observational data well at \( 0.05 < \dot{m} < 0.2 \). It predicts a relatively higher value of \( L_{\text{bol}}/L_x \) than that observed at \( \dot{m} > 0.2 \), which means that the corona is still energy inadequate for the X-ray emission. We also find that \( \beta_0 = 100 \) is suitable for the observation at \( \dot{m} > 0.2 \), whereas the model with \( \beta_0 = 100 \) predicts larger X-ray emission, i.e., less \( L_{\text{bol}}/L_x \) than observed for \( \dot{m} < 0.2 \). However, \( L_{\text{bol}}/L_x \) is always constant with \( \beta_0 = 50 \) and \( \beta_0 = 10 \) for different \( \dot{m} \), which is also not consistent with the observational results. In general, we suggest that \( \beta_0 \) should be about 100–200 with \( \alpha = 0.3 \) in the accretion disk for hard X-ray emission in luminous AGNs. Combined with the averaged energy fraction for \( \beta_0 = 100–200 \) shown in the upper panel of Figure 3, we suggest that larger than about 30% of the total gravitational energy is needed to be carried into the corona through magnetic reconnection in luminous AGNs.

4. DISCUSSION

4.1. The Relation between \( \alpha \) and \( \beta \)

Simulation works show that the viscous coefficient \( \alpha \) increases with the decreasing of \( \beta \) and their product remains nearly constant (e.g., Blackman et al. 2008; Guan et al. 2009; Hirose et al. 2009; Sorathia et al. 2012). Blackman et al. (2008) showed that the product is 0.5. However, the values of \( \alpha \) and \( \beta \) vary from one simulation to the other (Yuan & Narayan 2014). Besides, the value of \( \alpha \) in simulations also deviates from the value constrained by observation (King et al. 2013; Liu & Taam 2013).

The effect of magnetic field on the accretion flow is commonly investigated by changing the value of \( \beta \) for certain \( \alpha \) (Qian et al. 2007; Li & Begelman 2014). In our present work, we aim to overcome the inadequate energy in the corona of luminous AGNs and suppose that the corona is formed through the magnetic reconnection process. Given \( \alpha = 0.3 \), as in the observational result, we change the value of \( \beta_0 \) to find the proper magnetic field in accretion flow to fit the observed X-ray emission in luminous AGNs. It is found that the thin disk changes from being radiation pressure dominated to being gas pressure dominated as the magnetic field increases.
Correspondingly, the spectrum becomes harder for larger magnetic field. We also find an appropriate value of \( \beta_0 \) for different \( \alpha \). The relations between \( L_{\text{bol}} / L_\alpha \) and \( \dot{m} \) for different \( \alpha \) and \( \beta_0 \) in our model, which fit well with the observed data, are shown in Figure 6. It is found that for \( \alpha = 0.1 \) (red lines), \( \beta_0 \) is about 500, whereas \( \beta_0 \) decreases to about 50 for \( \alpha = 0.9 \) (dark cyan lines). This means that larger \( \alpha \) requires stronger magnetic field, which is roughly consistent with the MHD simulation results.

4.2. Is the Corona Strongly Magnetic Field Supported?

In our present work, we suppose that the magnetic field is generated at the midplane of the disk. The magnetic loops erupt into the corona because of the buoyancy instability and reconnect with other loops. Therefore, the magnetic flux is released to heat electrons in the corona. Similar to the structure of the solar corona, the low-\( \beta \) corona is also dynamically controlled by the magnetic field whose footpoints are embedded in buoyantly unstable, \( \beta \sim 1 \) plasma (Shibata et al. 1989; Di Matteo 1998). Miller & Stone (2000) found that the strongly magnetized and stable corona with \( \beta \lesssim 0.1 \) can be formed through turbulence in the disk with the initial weak magnetic field. \( \beta \) varies by about 3 orders of magnitude from the corona to the disk midplane. We find that \( \beta_0 \approx 50–500 \) with \( \alpha = 0.9–0.1 \) is suitable for the X-ray emission in luminous AGNs. When \( \beta_0 \approx 50–500 \), \( \beta \) approaches about 50–500 in the disk because of the disk being dominated by gas pressure. According to the vertical distribution of magnetic field found in Miller & Stone (2000), we can roughly estimate that \( \beta \sim 0.05–0.5 \) in the corona. This might indicate that the magnetic parameter \( \beta \) in the corona of luminous AGNs is less than that in LLAGNs found by Qiao & Liu (2013). They fitted the X-ray observational results in LLAGNs within the framework of the disk evaporation model and found that the magnetic field in the corona should be weak, i.e., \( \beta = 4–19 \).

4.3. Comparing with Other Hybrid Disk-corona Models

As shown by the corona energy Equation (6), it seems that the corona is sensitively affected by the amount of energy carried by the magnetic reconnection. In other words, the value of magnetic pressure \( P_B \) determines the structure and spectral features of the disk corona.

In Cao (2009) and You et al. (2012), they constructed a disk-corona model with three different types of magnetic stress tensor. The corona is two-temperature. The temperature of the ions is set to be 0.9 of the virial temperature, and electrons are heated through Coulomb collision with ions. It was tested that the magnetic stress tensor as \( \tau_{eB} = \gamma P_B \) always leads to constant \( L_{\text{bol}} / L_\alpha \) for different accretion rates. At the lowest accretion rate, the photon indices stay between 2.0 and 2.2. In our work, we take \( \beta_0 = (P_{\text{rad}} + P_{\text{ke}}) / P_B \) and assume that the electron is directly heated by the energy being released in the process of magnetic reconnection. It seems that there is a relation between \( \alpha \) (in that work) and \( \beta_0 \), i.e., \( \beta_0 = \frac{1}{\alpha} - 1 \). For \( \alpha = 0.3 \), \( \beta_0 \) should be 2.33 in our work. We can compare the value of \( \Gamma_{2,10 \text{ keV}} \) and \( L_{\text{bol}} / L_\alpha \) for \( \beta_0 = 10 \) (the same magnitude order as 2.33) with the results found in Cao (2009). For \( \beta_0 = 10 \), nearly all of the total gravitational energy is carried into the corona by the efficiently magnetic reconnection process, and the strongest corona is formed. In fact, it is also found that \( \Gamma_{2,10 \text{ keV}} \) and \( L_{\text{bol}} / L_\alpha \) hardly change with accretion rate, which is similar to the results found in Cao (2009). However, when \( \beta_0 > 10 \), the magnetic field is weaker than the case of \( \beta_0 = 10 \) for the same accretion rate. Thus, the total spectrum of the disk corona becomes softer with weaker magnetic field.

We note that the hard X-ray photon index \( \Gamma_{2,10 \text{ keV}} \) is always larger than 2.0 at the lowest accretion rate considered in our model. However, there are many luminous AGNs whose \( \Gamma_{2,10 \text{ keV}} < 2.0 \) (Yang et al. 2015). These sources might accrete through the clumpy two-phase accretion flow or accretion flows with coronas condensing into disks (Liu et al. 2007, 2015; Liu & Taam 2009; Qiao & Liu 2013; Yang et al. 2015). The main reason might be the difference in the soft photon field for inverse Compton scattering in the hot corona. In our present work, both the reprocessed corona photons and the intrinsic disk photons are included for the inverse Compton scattering. Even though nearly all the gravitational energy is carried into the corona, the continuous accretion disk absorbs the backward inverse Compton emission and the gas in the chromosphere is efficiently heated, which results in sufficient soft photons for the Compton cooling in the corona. For the clumpy cold gas or the condensation model, the weak disk only contributes a few soft photons to cool the corona, which in turn leads to harder X-ray spectrum.

4.4. Jet in Luminous AGNs

The jet is a very common feature in AGNs. However, the formation of jets is still a debated issue. Ballantyne (2007) investigated the accretion geometry of the radio-loud AGNs and suggested that there are three conditions affecting the jet launching: “a rapidly spinning black hole, an accretion flow with a large ‘H/R’ ratio, and a favorable magnetic field geometry.” In recent years, observational work on the correlation index \( \xi_{\text{RX}} \) between the radio luminosity \( L_R \) and hard X-ray luminosity \( L_{\text{X}} \) has provided more clues on the relation between the jet and the accretion flows (Merloni
et al. 2003; Falcke et al. 2004; Wu et al. 2013). It is found that the formation of a jet is related to the hot plasma in the vicinity of the black hole, in the form of either ADAF at low accretion rates or a disk corona at high accretion rates (e.g., Yuan et al. 2008; Cao 2014; Huang et al. 2014; Sun et al. 2015; Gu et al. 2015; Zhang et al. 2015). These hot accretion flows are always geometrically thick with $H \sim R$. In our model, since the detailed configuration of the magnetic field is not clear, we neglect the jet/outflow escaping from the corona. If a rapidly spinning black hole exists in the center, we can suspect that this magnetic-energy-sustained corona might help in launching the jet in luminous AGNs. The jet formation may also help reduce the downward reprocessing in the cool disk, which will also affect the X-ray emission of the corona. This issue will be studied in future work.

5. CONCLUSION

We revisit the structure and the emergent spectrum of a disk corona heated by the reconnection of magnetic field generated in the disk by dynamo action and emerging into the corona. We studied the effect of the magnetic field on the structure and spectrum of the model with various $\beta_0$ for $\alpha = 0.3$. It is found that the thin disk changes from being radiation pressure dominated to being gas pressure dominated as the magnetic field increases, which smoothly joins the two types of solutions together in Liu et al. (2002b, 2003). We find that the energy fraction gradually decreases from 0.95 to 0.3 when the accretion rate increases from 0.03 to 0.5 for $\beta_0 \sim 100$–200. Correspondingly, the hard X-ray spectrum becomes softer at higher accretion rate, which is consistent with the observed results. However, the disk is dominated by the radiation pressure, and the corona is still energy inadequate for the hard X-ray emission with $\beta_0 \gg 200$. For $\beta_0 < 50$, the disk is absolutely dominated by gas pressure and the energy fraction $f \sim 1.0$. The spectrum hardly changes with accretion rate, which is the same as the hard spectrum found in Liu et al. (2003).

We thank the referee for very useful suggestions and comments. This work is supported by the National Natural Science Foundation of China (grant Nos. 111303046, 11330386, 11673026, and U1231203), the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences (grant No. XDB09000000) and Gravitational Wave Pilot B (grant No. XDB23040100). Supported by the National Program on Key Research and Development Project (grant No. 2016YFA0400804).