Probing the Peculiar Behavior of GRS 1915+105 at Near-Eddington Luminosity

Kiki Vierdayanti\textsuperscript{1}, Shin Mineshige\textsuperscript{1}, and Yoshihiro Ueda\textsuperscript{1}

\textsuperscript{1}Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502

ki@kusastro.kyoto-u.ac.jp

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Abstract

To understand the nature of supercritical accretion, we systematically analyze the RXTE/PCA data of GRS 1915+105 in its quasi-steady states, by choosing data with small variability during 1999 – 2000. We apply a multicolor disk plus a thermal Comptonization model and take into consideration accurate interstellar absorption, a reflection component (with an iron-K emission line), and absorption features from the disk wind self-consistently. The total luminosity ranges from \( \sim 0.2L_{\text{E}} \) to slightly above \( L_{\text{E}} \). There is a strong correlation between the inner disk temperature and the fraction of the disk component. Most of the Comptonization-dominated (> 50% total flux) spectra show \( T_{\text{in}} \sim 1 \text{ keV} \) with a high electron temperature of > 10 keV, which may correspond to the very high state in canonical black hole X-ray binaries (BHBs). By contrast, the disk-dominated spectra have \( T_{\text{in}} \sim 2 \text{ keV} \) with a low temperature (< 10 keV) and optically thick Comptonization, and show two separate branches in the luminosity vs. innermost temperature (\( L \propto T_{\text{in}}^4 \)) diagram. The lower branch clearly follows the \( L \propto T_{\text{in}}^3 \)-track. Furthermore, applying the extended disk blackbody (or p-free disk) model, we find that 9 out of 12 datasets with disk luminosity above 0.3\( L_{\text{E}} \) prefer a flatter temperature gradient than that in the standard disk (\( p < 0.7 \)). We interpret that, in the lower branch, the disk extends down to the innermost stable circular orbit, and the source is most probably in the slim disk state. A rapidly spinning black hole can explain both the lack of the \( L \propto T_{\text{in}}^2 \)-track and a high value of spectral hardening factor (\( \sim 4 \)) that would be required for a non-rotating black hole. The spectra in the upper branch are consistent with the picture of a truncated disk with low temperature Comptonization. This state is uniquely observed from GRS 1915+105 among BHBs, which may be present at near-Eddington luminosity.

Key words: accretion, accretion disks — black hole physics — X-rays: individual (GRS 1915+105)

1. Introduction

The dynamics and emission properties of supercritical (or super-Eddington) accretion flows have been long-standing issues since the 1970s (Shakura and Sunyaev 1973). Theoretical studies on supercritical accretion are far from being complete due to the complex interaction between radiation and matter, despite recent progress in numerical simulations (e.g. Ohsuga et al. 2009). From observational studies, supercritical accretion appears to be present in some extragalactic objects, such as Narrow-line Seyfert 1 galaxies (NLS1s) and Ultraluminous X-ray sources (ULXs) (Kato et al. 2008, and references therein). In some NLS1s, the black hole mass can be estimated by means of reverberation mapping (e.g. Wandel et al. 1999; Kaspi et al. 2000). In the case of ULXs, however, the black hole mass is unknown and thus remains controversial. Nevertheless, their luminosity is higher than the Eddington luminosity of a stellar mass black hole. Black hole mass is the key to initially identifying a supercritical accreting system since the Eddington luminosity depends only on the black hole mass. In order to do a comprehensive study on supercritical accretion processes, we need an object whose black hole mass can be well-constrained. In addition, we also need adequate observational data.

One of the best objects for the study of supercritical accretion is the Galactic microquasar, GRS 1915+105. GRS 1915+105 has been active since its discovery by the WATCH all-sky X-ray monitor on \textit{GRANAT} (Castro-Tirado et al. 1992; 1994) on 1992 August 15. Its distance and inclination angle have been estimated from its superluminal jets (Mirabel and Rodríguez 1994) to be 12.5±1.5 kpc (see also Chaty et al. 1996; Dhawan et al. 2000) and 70° ± 2°, respectively. Dozens of types of peculiar variability in the X-rays have been observed (see Belloni et al. 2000; Klein-Wolt et al. 2002; Hannikainen et al. 2005), most of which have never been observed in other Galactic X-ray sources, including other known microquasars. GRS 1915+105 is thus known to be a peculiar X-ray source in our Galaxy. The jet feature and the variability of GRS 1915+105 are believed to be an important key to studying the coupling between jets and accretion disks in general (e.g. Mirabel et al. 1998; Neilsen and Lee 2009).

While optical observations are severely hampered since GRS 1915+105 is located close to the Galactic plane at \( l = 45.37^\circ, b = -0.22^\circ \) (Castro-Tirado et al. 1994), observations at other wavelengths prove to be quite fruitful. From infrared spectroscopy, GRS 1915+105 was suggested to be a low-mass X-ray binary (Castro-Tirado et al. 1996). This result is further supported by Greiner et al. (2001a) and
they also suggested that the donor star is a K – M giant with a narrow mass range $\sim 1.0 – 1.5 M_\odot$. The dynamical mass estimation results in a compact object of $14 \pm 4 M_\odot$ (Greiner et al. 2001b). This classifies GRS 1915+105 as the most massive black hole X-ray binaries (BHBs) in our Galaxy (for extragalactic BHBs, see, e.g. Orosz et al. 2007; Prestwich et al. 2007).

Since the dynamical mass can be estimated, GRS 1915+105 is known to prefer being in a state where the luminosity is close to or even exceeding its Eddington luminosity (Done et al. 2004), which corresponds to the supercritical accretion process. Provided that GRS 1915+105 does really exhibit supercritical accretion, it can be used as a guide for the interpretation of other supercritical accreting objects that lack sufficient data for a comprehensive study.

We use archival RXTE data mainly from 1999 to 2000 and apply the so-called disk-corona model to the extracted spectra. Our focus on the study of the supercritical accretion in GRS 1915+105 distinguishes this work from other previous extensive studies (e.g. Done et al. 2004; McClintock et al. 2006; Middleton et al. 2006). We also need to stress that we do not attempt to explain the nature of GRS 1915+105 with its richness of variability on timescales from years down to milliseconds (see, e.g. Morgan et al. 1997; Belloni et al. 2000) and its non-canonical soft and hard states. Those studies have been done by many authors (see, e.g. Belloni et al. 1997a, b) and the most recent work can be found in Rodriguez et al. (2008a, b). On the contrary, we choose data from when the source was more or less stable, without strong variability features as classified in Belloni et al. (2000). The constraint on the mass of GRS 1915+105 from dynamical estimates helps us to study the detailed relation between the X-ray spectra and mass accretion rate in terms of its luminosity during its supercritical accretion state.

The layout of this paper is as follows: We describe our data sample in section 2, and continue with describing the model and the fitting analysis in section 3 and 4, respectively. Section 5 is devoted to the discussion, and finally section 6 concludes the paper. Throughout our study we adopt the following values: a distance of 12 kpc, an inclination angle of 70°, and a black hole mass of $14 M_\odot$.

2. Data

For the purpose of the present study, we deliberately choose the data when the source was bright and more or less stable, that is when no large flux variations are observed. Therefore, we only choose data from classes $\phi$, $\delta$, and $\chi$ from the 12 known classes of X-ray variability in GRS 1915+105 (Belloni et al. 2000). The variability selection is made by eye from the lightcurve available through the RXTE standard products.

GRS 1915+105 has been monitored by RXTE since 1996, once a week on average. We select the RXTE data of GRS 1915+105 between January 1999 and May 2000. This range of observation times contains data from epochs 3B, 4 and 5, and consists of a total of 216 datasets to be examined. Focusing on data with small variability, we manage to keep 23 datasets for further fitting analysis.

Fig. 1. RXTE/ASM lightcurve. The minimum count for soft state detection, 30 cts/s, is marked with the dotted line. The arrows mark the datasets of our final sample (see text).
Table 1. The final sample.

| Dataset | Observation ID | Observation Date   | Observation Time | Duration (s) | Class (State) |
|---------|----------------|--------------------|------------------|--------------|---------------|
| 1       | 20402-01-55-00 | 1997-11-17         | 05:27:06.6       | 15378        | $\delta$ (B,(A)) |
| 2       | 30703-01-08-00 | 1998-02-14         | 23:51:55.3       | 4868         | $\phi$ (A)    |
| 3       | 40703-01-14-01 | 1999-05-08         | 04:33:18.7       | 4319         | $\delta$ (B,(A)) |
| 4       | 40703-01-14-02 | 1999-05-08         | 06:09:19         | 3085         | $\delta$ (B,(A)) |
| 5       | 40703-01-20-02 | 1999-07-03         | 01:51:37.7       | 4190         | $\chi$ (C)    |
| 6       | 40703-01-22-01 | 1999-07-21         | 01:57:09.5       | 2699         | $\chi$ (C)    |
| 7       | 40703-01-28-00 | 1999-08-28         | 18:30:00.6       | 2891         | $\delta$ (B,(A)) |
| 8       | 40703-01-34-00 | 1999-10-20         | 17:09:35.1       | 1862         | $\delta$ (B,(A)) |
| 9       | 40703-01-35-00 | 1999-10-25         | 15:07:08.5       | 3108         | $\chi$ (C)    |
| 10      | 40703-01-36-00 | 1999-11-02         | 14:48:37.4       | 2415         | $\chi$ (C)    |
| 11      | 40703-01-38-03 | 1999-11-15         | 14:09:02.3       | 3420         | $\chi$ (C)    |
| 12      | 40703-01-38-02 | 1999-11-15         | 15:43:01.6       | 3540         | $\chi$ (C)    |
| 13      | 40703-01-38-01 | 1999-11-15         | 17:13:01.6       | 3900         | $\chi$ (C)    |
| 14      | 40703-01-39-00 | 1999-11-21         | 12:09:00.9       | 3901         | $\delta$ (B,(A)) |
| 15      | 40703-01-40-00 | 1999-12-01         | 11:45:03.2       | 3900         | $\chi$ (C)    |
| 16      | 40703-01-40-02 | 1999-12-01         | 14:56:22.3       | 2912         | $\chi$ (C)    |
| 17      | 40703-01-40-03 | 1999-12-01         | 16:30:03.5       | 3240         | $\chi$ (C)    |
| 18      | 40702-01-04-00 | 2000-02-05         | 05:58:34.5       | 3004         | $\chi$ (C)    |
| 19      | 40403-01-10-00 | 2000-02-14         | 10:28:11.1       | 2677         | $\chi$ (C)    |
| 20      | 50703-01-10-01 | 2000-05-17         | 03:15:10.7       | 2753         | $\chi$ (C)    |

3. Fitting Models

In this section we describe the models used in our analysis. We fit all the data (3 – 25 keV) with an absorbed disk-corona model employing two different disk models, one for the whole dataset and one applied only to a subset. Details are as follow:

3.1. Absorption model

We model the absorption by the interstellar (as well as circumstellar) medium by using the Tuebingen-Boulder interstellar medium absorption model (’tbvarab’ in XSPEC11). The constraint on the elemental abundance in the direction of GRS 1915+105 is adopted from the recent study by Ueda et al. (2009). By using data from Chandra and RXTE, they make a robust constraint of the interstellar (plus circumstellar) absorption components towards GRS 1915+105. This is, in a sense, an improvement in the study of GRS 1915+105 since the absorption model significantly affects the energy range of the emission from a black hole accretion disk. The hydrogen column density is fixed at $2.78 \times 10^{22}$ cm$^{-2}$ with metal abundances larger than solar assumed. This value is smaller than the commonly adopted value for this source in which solar abundances are assumed, $4.7 \times 10^{22}$ cm$^{-2}$ (Chaty et al. 1996).

3.2. Disk models

We fit the disk component of the whole dataset with a multicolor disk (MCD) model (Mitsuda et al. 1984; Makishima et al. 1986), a mathematical approximation model of the standard accretion disk (Shakura and Sunyaev 1973).

Given that some of our data have a luminosity close to or even above the Eddington luminosity, we also fit a subset of the whole dataset with another disk model, the extended disk blackbody (extended DBB) model (the so-called $p$-free disk model; Mineshige et al. 1994). This subset contains data with disk-dominated spectra (see section 4.1.2 for details).

The standard theory of accretion disks gives an effective temperature profile which is proportional to $r^{-3/4}$, where $r$ is the disk radius. As the luminosity approaches the Eddington luminosity, the standard accretion disk model breaks down and should be replaced by the supercritical accretion model (e.g. the slim disk model). In the supercritical accretion regime, the temperature profile is expected to become flatter at small radii; this is caused by the advective motion of the trapped radiation. In the extended DBB model, the effective temperature profile is assumed to be $T_{\text{eff}} \propto r^{-p}$, where $p$ is now a fitting parameter. In principle, by using the extended DBB model, we can distinguish the slim disk from that of the standard disk by spectral fitting (e.g. Vierdayanti et al. 2006; Okajima et al. 2006; Tsunoda et al. 2006). Furthermore,
mass loss due to radiation pressure-driven outflow is also known to modify the temperature profile (Shakura and Sunyaev 1973; Poutanen et al. 2007; Takeuchi et al. 2009). For a mass accretion rate of $\dot{M} \propto r^s$, where $s$ is a positive parameter, the effective temperature profile follows $T_{\text{eff}} \propto r^{-(3-s)/4}$.

3.3. Thermal Comptonization model

We add a thermal Comptonization model to the disk models mentioned above (‘nthcomp’ in XSPEC11: Zycki et al. 1999) to fit the high energy part of the spectrum (> 10keV), that is, the coronal component. Most of our data prefer low electron temperature values (< 10 keV) and nthcomp is one of the better Comptonization models for such cases. It is also a consistent model for our present study since the seed photons can have a disk spectrum (compare, for example, with ’comptt’ in XSPEC11 in which the seed photons are assumed to have a Wien spectrum). The temperature of the seed photons of the corona is linked to the disk temperature, by assuming that the seed photons are coming from the disk.

To make the fitting realistic, we also consider the reflection of up-scattered photons by the disk based on the code by Magdziarz & Zdziarski (1995) (pexriv in XSPEC11). Here, however, we have to apply several assumptions. We assume that the disk emissivity profile is proportional to $r^{-s}$, where $r$ is the disk radius. Other important parameters for the reflection component are the reflection amplification ($\equiv \Omega/2\pi$), the ionization parameter, $\xi$ ($\equiv L/nr^2$, where $L$ is the luminosity and $n$ is density), and the inner and outer radius of the reflecting area of the disk, $R_{\text{in}}$ and $R_{\text{out}}$, respectively. The iron-K emission line is included in the model.

Throughout our study we treated these reflection parameters as free parameters except for $R_{\text{out}}$ that is always fixed at $10^5 r_g$ ($r_g \equiv GM/c^2$). We find that most of our data prefer low $R_{\text{in}}$ (<100$r_g$), inferring significant reflection from the inner part of the disk although its error is large. We thus fix $R_{\text{in}}$ at 40$r_g$, adopting the typical value from the previous study by Done et al. (2004). Low values of $\xi$ are also preferred by our data. Therefore, we adopt the value of $\xi$ as found in Ueda et al. (2009); that is, we fix $\xi$ at 40. The overall fitting results, however, do not sensitively depend on our choice of $\xi$. Finally, we treat $\Omega/2\pi$ as the only free parameter of the reflection component. We, however, limit the maximum value of $\Omega/2\pi$ to 1.

Several studies have reported the discovery of absorption line features from this source (see, e.g. Kotani et al. 2000). We find that the fitting residuals improved significantly when we include an iron edge (modeled with ‘edge’ in XSPEC11) to account for absorption features of Fe XXVI ions as done in Ueda et al. (2009). We thus expect that H-like absorption line of iron to be present in the spectra of our final sample. Therefore, we include an absorption line at 7.0 keV (Kα). Regarding the absorption lines, we use a negative Gaussian model. We fix the line width at 40 eV but left the normalization of this model as a free parameter. In addition, this normalization is also linked to the absorption depth of the iron to make a more physical fitting. This is necessary because both the equivalent width of an absorption line and the optical depth of an edge are proportional to the normalization of the Gaussian, provided that the absorption equivalent width is in a linear part of the curve of growth (see Kotani et al. 2000).

4. Fitting Results and Analysis

As mentioned earlier, the energy range for fitting is set to be 3 – 25 keV (PCA data only) and there are 25 datasets in our final sample (see table 1). We first fit all the datasets with the (MCD+nthcomp) model. See Figure 2 for two representative samples of disk-dominated spectra (right panel) and Comptonization-dominated spectra (left panel).
A color-color diagram of our data sample is given in figure 3. We follow Done and Gierliński (2003) in defining the soft and hard colors. That is, the soft color is defined as the ratio of unabsorbed fluxes in the $4 - 6.4$ and $3 - 4$ keV bands, while the hard color as the ratio of unabsorbed fluxes in the $9.7 - 16$ and $6.4 - 9.7$ keV bands. As mentioned in section 2, we also include two datasets which were previously studied by Done et al. (2004). Datasets 1 and 2 in this work correspond to datasets 6 and 7 of Done et al. (2004). The upper left group in figure 3 consists of data with Comptonization-dominated spectra with one exception, dataset 25. On the other hand, the lower right group mostly consists of data with disk-dominated spectra with two exceptions, datasets 11 and 12. Dataset 2 is Comptonization-dominated when fitted with our model as opposed to the previous study.

A second disk model (the extended DBB model) was applied to the subset in the lower right of the color-color diagram (see figure 3, red circle) and dataset 25 from the upper left group. In total, we fit 12 datasets with the (extended DBB model+nthcomp) model. We obtain acceptable values of reduced chi-squared, $\chi^2$/d.o.f. where d.o.f. means degrees of freedom, for overall fitting (except dataset 2, where $\chi^2$/d.o.f.$>$ 1.5). In fact, in most cases, the $\chi^2$/d.o.f. is rather low. We found that this is caused by the moderately large systematic error value (1.5%) included in the fitting. The results from fitting all the data with the (MCD+nthcomp) model are given in tables 2 and 3, while the results from the (extended DBB+nthcomp) model are given in table 4. The unfolded spectra of all datasets in our final sample, together with the corresponding components of the models, are given in figures 4 and 5 for the (MCD+nthcomp) model and figure 6 for the (extended DBB+nthcomp) model.

### 4.1. Disk Components

#### 4.1.1. MCD components

Our final sample has $kT_{\text{in}}$ ranges between $0.7 - 2$ keV while the total luminosity ranges from $\sim 0.15 - 1.04 L_E$, where $L_E$ is the Eddington luminosity ($= 1.5 \times 10^{38} (M/M_{\odot})$ erg s$^{-1}$). Data with $kT_{\text{in}}$ within $1.5 - 2$ keV are mostly those with disk-dominated spectra (see figure 7, filled stars). The inner disk temperature in our sample is too high for a $14M_{\odot}$ non-rotating black hole. A rotating black hole is, thus, often suggested to explain a too high disk temperature phenomena in this source (McClintock et al. 2006; Middleton et al. 2006; Zhang et al. 1997). Caution needs to be taken for some Comptonization-dominated data. As shown in table 2, some of these Comptonization-dominated data (i.e. datasets 16, 17, 18, 20, 21, and 23) have a very low disk fraction, $\sim 0$. In this case, the values of the disk temperature from the fitting become less reliable since the disk contribution is negligible.

The disk inner radius can be derived from the normalization of the MCD model, i.e., normalization $\equiv ((D/10\text{kpc})^2/(r_{\text{in}} \text{ [kpc]})^2) \times \cos i$, where $D$ is the distance to the source in kpc and $i$ is the inclination angle of the system. Note that $r_{\text{in}}$ is the apparent inner disk radius without relativistic ($\zeta$) and spectral hardening factor ($\kappa$) corrections. The true inner radius can be obtained by using the following formula: $r_{\text{in}}^{\text{true}} = \kappa^2 r_{\text{in}}^{\text{apparent}}$ (see Kubota et al. 1998). That is, when we mention $r_{\text{in}}$, we refer to the $r_{\text{in}}^{\text{true}}$ throughout this paper unless stated otherwise. However, since we use a disk-corona model, we have to take into account the effect of the thermal Comptonization in the spectrum. We calculate the apparent disk inner radius by using the formula (A1) shown in Kubota and Makishima (2004) in which spherical geometry is assumed for the thermal Comptonization emission. However, here we assume that half the photons in the corona are injected back into the accretion disk due to the large optical depth, as done in Ueda et al. (2009).

By using this formula, the obtained true inner radius of the disk is mostly within $\sim 0.5 - 7r_S$, where $r_S$ is about 42 km for a $14M_{\odot}$ black hole ($r_S \equiv 2GM/c^2$ is a Schwarzschild radius), assuming a non-rotating black hole. Here we have used $\kappa = 1.7$ and $\zeta = 0.412$ to derive these true inner radii. We find that the data whose disk fraction is larger than 50% of the total component have a lower inner disk radius, $< 1r_S$ (see figure 7, filled stars). If, however, we choose higher $\kappa$, say $\kappa = 3$ (note that in figure 10 the upper branch in the lower panel coincides with the line of $\kappa = 3$ for a non-rotating black hole), $r_{\text{in}}$ would range within $\sim 1.5 - 22r_S$, that is $(3/1.7)^2$ times larger than that of $\kappa = 1.7$ case.

We find a strong correlation between the disk parameters and the fraction of the disk component. As shown in figure 7, the inner disk temperature increases as the fraction of the disk component increase. The inner disk radius follows the opposite trend. We attempt to interpret this correlation in section 5.
Fig. 4. Unfolded spectra and model of datasets 1 – 12. The total, disk (MCD), and thermal Comptonization components are shown in green, magenta, and blue lines, respectively. The data, shown with red crosses, coincide with the total model.
Fig. 5. Same as figure 4 for datasets 13 – 25.
Table 2. MCD components of the fitting. The unit for $kT_{\text{in}}$ is keV. $r_{\text{in}}$ is not calculated from the MCD model normalization (see text). $F_{\text{disk}}$ and $F_{\text{disk}}^p$ are the 0.01 – 100 flux (10^{-8} \text{ erg cm}^{-2} \text{s}^{-1}) and the photon flux (in photon s^{-1} cm^{-2}) of the disk component, respectively. % Disk is the disk fraction on the spectrum in per cent. The values of $F_{\text{disk}}, F_{\text{disk}}^p, \%$ Disk, and $L_{\text{disk}}/L_E$ which are less than 10^{-5} are written as 0.

| Dataset | $kT_{\text{in}}$ | $r_{\text{in}}/r_S$ | $F_{\text{disk}}$ | $F_{\text{disk}}^p$ | % Disk | $L_{\text{disk}}/L_E$ | $\chi^2$/d.o.f |
|---------|------------------|-------------------|-----------------|-----------------|-------|----------------|----------------|
| 1       | $1.81_{-0.06}^{+0.1}$ | 0.50 ± 0.07 | 5.21 | 22.8 | 74.6 | 0.68 ± 0.20 | 0.22 |
| 2       | $1.06_{-0.09}^{+0.1}$ | 1.80 ± 0.25 | 0.95 | 6.77 | 29.0 | 0.12 ± 0.04 | 1.57 |
| 3       | $1.71_{-0.03}^{+0.03}$ | 0.57 ± 0.08 | 1.63 | 7.52 | 53.0 | 0.21 ± 0.06 | 0.46 |
| 4       | $1.74_{-0.02}^{+0.03}$ | 0.55 ± 0.07 | 1.68 | 7.61 | 53.5 | 0.22 ± 0.06 | 0.37 |
| 5       | $0.84_{-0.05}^{+0.08}$ | 3.45 ± 0.50 | 0.001 | 0.009 | 0.02 | 1E-4 ± 4E-5 | 0.52 |
| 6       | $0.89_{-0.15}^{+0.07}$ | 2.42 ± 0.35 | 0.47 | 3.98 | 13.7 | 0.06 ± 0.02 | 0.43 |
| 7       | $2.05_{-0.03}^{+0.02}$ | 0.21 ± 0.03 | 3.70 | 14.4 | 87.3 | 0.48 ± 0.14 | 0.42 |
| 8       | $1.87_{-0.03}^{+0.04}$ | 0.49 ± 0.07 | 2.57 | 10.9 | 62.8 | 0.33 ± 0.10 | 0.28 |
| 9       | $1.93_{-0.03}^{+0.04}$ | 0.49 ± 0.07 | 2.46 | 10.1 | 59.5 | 0.32 ± 0.10 | 0.51 |
| 10      | $1.93_{-0.03}^{+0.04}$ | 0.46 ± 0.06 | 2.66 | 11.0 | 63.0 | 0.35 ± 0.10 | 0.57 |
| 11      | $1.57_{-0.04}^{+0.05}$ | 1.09 ± 0.15 | 1.87 | 9.52 | 32.8 | 0.24 ± 0.07 | 0.20 |
| 12      | $1.68_{-0.03}^{+0.04}$ | 1.06 ± 0.15 | 2.48 | 11.7 | 36.7 | 0.32 ± 0.09 | 0.30 |
| 13      | $1.73_{-0.03}^{+0.03}$ | 0.82 ± 0.11 | 4.09 | 18.6 | 57.3 | 0.53 ± 0.15 | 0.32 |
| 14      | $1.23_{-0.03}^{+0.03}$ | 1.64 ± 0.24 | 2.21 | 13.9 | 34.9 | 0.29 ± 0.08 | 0.25 |
| 15      | $1.26_{-0.03}^{+0.03}$ | 1.26 ± 0.18 | 1.34 | 8.27 | 33.5 | 0.17 ± 0.05 | 0.24 |
| 16      | $1.16_{-0.03}^{+0.08}$ | 3.37 ± 0.49 | 0 | 0 | 0 | 0 | 0.29 |
| 17      | $1.06_{-0.02}^{+0.12}$ | 4.12 ± 0.59 | 0 | 0 | 0 | 0 | 0.29 |
| 18      | $0.87_{-0.04}^{+0.04}$ | 4.93 ± 0.71 | 0 | 0 | 0 | 0 | 0.24 |
| 19      | $1.84_{-0.03}^{+0.03}$ | 0.48 ± 0.07 | 7.43 | 32.1 | 82.3 | 0.97 ± 0.28 | 0.43 |
| 20      | $0.86_{-0.04}^{+0.04}$ | 3.76 ± 0.54 | 0 | 0 | 0 | 0 | 0.38 |
| 21      | $1.04_{-0.02}^{+0.11}$ | 4.14 ± 0.60 | 0 | 0 | 0 | 0 | 0.37 |
| 22      | $0.76_{-0.04}^{+0.09}$ | 6.61 ± 0.95 | 0.28 | 2.81 | 2.85 | 0.04 ± 0.01 | 0.26 |
| 23      | $0.96_{-0.04}^{+0.11}$ | 2.72 ± 0.39 | 0 | 0 | 0 | 0 | 0.52 |
| 24      | $1.27_{-0.05}^{+0.05}$ | 1.33 ± 0.19 | 1.12 | 6.82 | 24 | 0.15 ± 0.04 | 0.40 |
| 25      | $1.51_{-0.03}^{+0.03}$ | 0.49 ± 0.07 | 0.98 | 5.1 | 51.1 | 0.13 ± 0.04 | 0.40 |
Table 3. Thermal Comptonization component of the fitting. The unit for $kT_e$ is keV. $F_{\text{THC}}$ and $F'_{\text{THC}}$ are the 0.01 – 100 keV flux (10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}) and the photon flux (in photon s^{-1} cm^{-2}) of the Comptonized component, respectively. $\tau$ is the scattering optical depth and $L$ is the total luminosity (see text).

| Dataset | $kT_e$ | $\Gamma$ | $F_{\text{THC}}$ | $F'_{\text{THC}}$ | $\tau_e$ | $\Omega/2\pi$ | $L/L_E$ |
|---------|--------|---------|----------------|-----------------|----------|----------------|---------|
| 1       | $3.08^{+0.07}_{-0.06}$ | 2.12^{+0.06}_{-0.06} | 1.77 | 4.83 | 9.00 | 0.69 | 0.76±0.22 |
| 2       | $3.34^{+0.20}_{-0.50}$ | 3.16^{+0.05}_{-0.05} | 2.31 | 12.6 | 5.09 | 1.00 | 0.23±0.06 |
| 3       | $10.6^{+2.54}_{-1.57}$ | 3.74^{+0.07}_{-0.06} | 1.44 | 5.35 | 1.88 | 4E-8 | 0.28±0.08 |
| 4       | $11.5^{+3.58}_{-2.01}$ | 3.75^{+0.08}_{-0.07} | 1.46 | 5.29 | 1.78 | 2E-6 | 0.28±0.08 |
| 5       | $17.1^{+2.32}_{-1.70}$ | 2.76^{+0.01}_{-0.01} | 4.25 | 23.0 | 2.10 | 0.30 | 0.19±0.05 |
| 6       | $25.0^{+0.0}_{-3.33}$ | 2.58^{+0.003}_{-0.01} | 2.94 | 13.4 | 1.78 | 0.41 | 0.19±0.06 |
| 7       | $3.38^{+0.08}_{-0.07}$ | 1.94^{+0.03}_{-0.03} | 0.54 | 1.22 | 9.64 | 1.00 | 0.51±0.15 |
| 8       | $4.60^{+0.25}_{-0.24}$ | 3.27^{+0.05}_{-0.06} | 1.52 | 5.10 | 3.99 | 0.41 | 0.40±0.12 |
| 9       | $6.30^{+0.75}_{-0.53}$ | 3.81^{+0.09}_{-0.08} | 1.67 | 5.71 | 2.64 | 0.30 | 0.39±0.11 |
| 10      | $3.61^{+0.11}_{-0.10}$ | 2.95^{+0.05}_{-0.04} | 1.56 | 5.00 | 5.31 | 0.49 | 0.42±0.12 |
| 11      | $3.38^{+0.07}_{-0.05}$ | 3.09^{+0.03}_{-0.02} | 3.84 | 15.0 | 5.19 | 0.21 | 0.41±0.12 |
| 12      | $5.71^{+0.49}_{-0.46}$ | 4.40^{+0.07}_{-0.09} | 4.29 | 17.4 | 2.32 | 0.27 | 0.51±0.15 |
| 13      | $5.53^{+0.56}_{-0.35}$ | 3.98^{+0.09}_{-0.07} | 3.05 | 11.5 | 2.72 | 0.37 | 0.67±0.19 |
| 14      | $25^{+0.0}_{-1.24}$ | 2.89^{+0.004}_{-0.02} | 4.12 | 16.4 | 1.49 | 0.12 | 0.47±0.14 |
| 15      | $16.6^{+2.93}_{-2.10}$ | 2.86^{+0.02}_{-0.02} | 2.67 | 10.5 | 2.03 | 0.21 | 0.29±0.08 |
| 16      | $25^{+0.0}_{-3.87}$ | 3.33^{+0.004}_{-0.02} | 9.94 | 49.8 | 1.18 | 0.24 | 0.44±0.13 |
| 17      | $14.4^{+1.55}_{-1.17}$ | 3.15^{+0.02}_{-0.01} | 10.6 | 56.2 | 1.95 | 0.27 | 0.47±0.14 |
| 18      | $11.7^{+0.85}_{-0.72}$ | 3.04^{+0.01}_{-0.01} | 9.09 | 53.3 | 2.37 | 0.31 | 0.40±0.12 |
| 19      | $7.51^{+0.69}_{-0.65}$ | 2.84^{+0.04}_{-0.04} | 1.60 | 4.77 | 3.52 | 0.51 | 1.04±0.30 |
| 20      | $11.2^{+0.25}_{-0.08}$ | 3.03^{+0.01}_{-0.01} | 5.01 | 29.7 | 2.46 | 0.32 | 0.22±0.06 |
| 21      | $15.6^{+1.95}_{-1.50}$ | 3.20^{+0.02}_{-0.02} | 14.4 | 71.6 | 1.80 | 0.27 | 0.64±0.18 |
| 22      | $10.6^{+0.69}_{-0.54}$ | 2.91^{+0.01}_{-0.01} | 9.66 | 62.1 | 2.70 | 0.42 | 0.47±0.13 |
| 23      | $25^{+0.0}_{-1.01}$ | 2.85^{+0.02}_{-0.02} | 3.47 | 17.9 | 1.51 | 0.29 | 0.15±0.04 |
| 24      | $14.1^{+1.62}_{-1.27}$ | 2.52^{+0.01}_{-0.01} | 3.54 | 12.0 | 2.76 | 0.12 | 0.30±0.09 |
| 25      | $21.2^{+3.81}_{-4.36}$ | 2.50^{+0.01}_{-0.02} | 0.94 | 2.10 | 2.69 | 4E-5 | 0.17±0.05 |
Fig. 6. Unfolded spectra and model of the disk-dominated data. The total, disk (p-free disk), and thermal Comptonization components are shown in green, magenta, and blue lines, respectively. The data, shown with red crosses, coincide with the total component. See text for details.
### 4.1.2. Extended disk blackbody components

For consistency, when the extended DBB model is used to fit the disk component, we modify the temperature profile of the seed photons in the thermal Comptonization model. That is, the temperature profile is set to be $T_{\text{outer}} \propto r^{-p}$, with $p$ ranging from 0.5 to 0.75, instead of using the MCD temperature profile.

We only fit a group of data in the lower right of color-color diagram (see figure 3, red circle) and dataset 25 from the upper left group (blue circle). That is, we only choose data with disk-dominated (or suspected, such as datasets 11 and 12) spectra. We are interested in finding deviations from the standard high/soft state spectra as the luminosity approaches or exceeds the Eddington luminosity. In total, we fit 12 datasets with the extended DBB model + modified thermal Comptonization model.

The unfolded spectra and all components of the model are shown in figure 6. Results of the fits are summarized in table 4. As shown in table 4 (and figure 6), the disk fraction of the twelve datasets is mostly larger than 75%. Moreover, disk fraction in datasets 11 and 12 increases significantly and even exceeds the fraction of the thermal Comptonization component.

The radial temperature gradient, $p$, is shown in column 3 of table 4. We can see that the $p$-values tend to deviate from 0.75. In fact, nine out of twelve datasets (1, 3, 4, 9, 11, 12, 13, 19, and 25) prefer a $p$-value which is less than 0.6 with less than 10% error. The disk temperature of most datasets tends to increase compared to those of the MCD + thermal Comptonization model, that is $kT_{\text{in}} \sim 1.8 - 2.1$ keV.

### 4.2. Thermal Comptonization Component

Here we will only focus on two important parameters from the thermal Comptonization model that we use in our present study. These parameters are the electron temperature, $kT_e$, and the power-law photon index, $\Gamma$. The electron temperature determines the high energy rollover. In addition, the low energy rollover is also considered and is parametrized by the seed photon temperature. In our present study, this seed photon temperature is equal to the inner disk temperature. The power-law photon index determines the slope between low and high energy rollovers.

We will first describe the results for the case where the disk component is modeled by MCD. With some few exceptions, data with $>50\%$ disk fraction prefer low electron temperature below 10 keV (see figure 8, filled stars). We, however, set the maximum limit at 25 keV for the electron temperature since, otherwise, it cannot be constrained by our data in some cases. It is important to note here that the error estimate for the electron temperature is, unlike other parameters, quite large. In other words, we should be very careful in making an interpretation based on the electron temperature results. The power-law photon index varies between 2 – 5 for most data regardless of the

| Dataset | $kT_{\text{in}}$ ($\pm$) | $p$ | $kT_e$ ($\pm$) | $\Gamma$ | % Disk | $L_{\text{disk}}/L_E$ | $L/L_E$ | $\chi^2$/d.o.f |
|---------|-------------------|-----|----------------|--------|--------|-------------------|---------|----------------|
| 1       | 1.85$^{+0.03}_{-0.03}$ | 0.69 ± 0.12 | 3.64 ± 0.76 | 2.93 ± 2.00 | 56.7 | 0.55 ± 0.16 | 0.70 ± 0.20 | 0.45 |
| 3       | 2.06$^{+0.01}_{-0.01}$ | 0.59 ± 0.02 | 8.09 ± 1.86 | 2.86 ± 0.77 | 85.0 | 0.48 ± 0.14 | 0.51 ± 0.15 | 0.92 |
| 4       | 2.11$^{+0.02}_{-0.02}$ | 0.59 ± 0.02 | 13.6 ± 3.60 | 2.93 ± 0.76 | 87.2 | 0.49 ± 0.14 | 0.51 ± 0.15 | 0.79 |
| 7       | 2.03$^{+0.02}_{-0.02}$ | 0.74 ± 0.05 | 8.28 ± 1.86 | 4.43 ± 0.75 | 54.2 | 0.30 ± 0.09 | 0.39 ± 0.11 | 0.67 |
| 8       | 1.91$^{+0.02}_{-0.02}$ | 0.72 ± 0.04 | 7.05 ± 1.15 | 4.05 ± 0.05 | 54.4 | 0.30 ± 0.09 | 0.39 ± 0.11 | 0.64 |
| 9       | 2.06$^{+0.02}_{-0.02}$ | 0.68 ± 0.03 | 25.0 ± 0.00 | 4.52 ± 0.09 | 67.9 | 0.40 ± 0.11 | 0.46 ± 0.13 | 0.78 |
| 10      | 1.94$^{+0.02}_{-0.02}$ | 0.75 ± 0.06 | 5.13 ± 0.11 | 3.94 ± 0.05 | 48.7 | 0.27 ± 0.08 | 0.36 ± 0.10 | 0.67 |
| 11      | 2.14$^{+0.03}_{-0.01}$ | 0.56 ± 0.01 | 4.92 ± 0.07 | 3.15 ± 0.03 | 83.1 | 1.06 ± 0.30 | 1.13 ± 0.33 | 1.03 |
| 12      | 2.03$^{+0.15}_{-0.15}$ | 0.6 ± 0.04 | 9.34 ± 6.07 | 3.66 ± 0.19 | 87.6 | 1.06 ± 0.30 | 1.11 ± 0.32 | 0.69 |
| 13      | 1.92$^{+0.05}_{-0.01}$ | 0.65 ± 0.07 | 6.92 ± 17.3 | 3.61 ± 4.33 | 81.5 | 0.89 ± 0.25 | 0.96 ± 0.28 | 0.76 |
| 19      | 1.92$^{+0.14}_{-0.14}$ | 0.69 ± 0.07 | 6.00 ± 5.19 | 2.41 ± 1.56 | 88.9 | 1.12 ± 0.32 | 1.17 ± 0.34 | 0.28 |
| 25      | 1.95$^{+0.12}_{-0.04}$ | 0.55 ± 0.05 | 6.94 ± 0.35 | 1.91 ± 0.10 | 76.0 | 0.33 ± 0.10 | 0.37 ± 0.11 | 0.60 |
Fig. 7. $kT_{in}$ and $r_{in}/r_S$ obtained from the fitting. The dotted line in the lower panel shows $kT_{in} = 1$ keV. The dotted lines in the upper panel mark $r_{in}/r_S = 1$ and 3. Comptonization-dominated data are shown as open squares while disk-dominated data are shown as filled stars.

disk fraction. Despite its relatively small errors, no clear trend is found which left no room for further speculation (see figure 8).

In figure 9, the electron scattering optical depth, $\tau_e$, is calculated from $T_e$ and $\Gamma$ by following Sunyaev and Titarchuk (1980):

$$\tau_e = \sqrt{2.25 + \frac{3}{(T_e/511\text{keV})[(\Gamma + 0.5)^2 - 2.25]}} - 1.5. \quad (1)$$

The lines show constant $\Gamma = 2, 2.5, 3, 3.5, 4,$ and 4.5, from top to bottom. All data prefer an electron scattering optical depth between 1 and 10, mostly greater than 2.

In the case where the disk component is modeled by extended DBB, the electron temperatures tend to be higher but mostly still less than 10 keV, in agreement with those of the MCD fits (see tables 3 and 4). The power-law photon index, $\Gamma$, remains within the same range as those of the MCD fits although the values are not always similar. We conclude that both the MCD and the extended DBB model prefer low temperatures ($< 20$ keV) and thus optically thick ($\tau > 2$) corona (since $\Gamma$ values do not vary so much).

Fig. 8. $kT_e$ and $\Gamma$ obtained from the fitting (see text). The dotted line in the lower panel represents $kT_e = 10$ keV.

Fig. 9. $\tau$ vs. $kT_e$ (see text). The lines are for constant value of $\Gamma$, that is $\Gamma = 2, 2.5, 3, 3.5, 4, 4.5$, from top to bottom. The open squares are data with Comptonization-dominated spectra, while the filled stars are those with disk-dominated spectra.
4.3. X-ray Hertzsprung-Russell (HR) Diagram

One of the most general properties of accreting black hole systems is that they follow a $L \propto T_{\text{eff}}^4$-track (see, e.g. Gierliński and Done 2004) in a luminosity versus inner disk temperature diagram (an X-ray Hertzsprung-Russell (HR) diagram) during the high/soft state (i.e. when the disk component dominates the soft X-ray spectrum). This property means that as the disk temperature and luminosity change, the inner radius of the disk remains constant (Makishima et al. 1986; Ebisawa et al. 1991; Dotani et al. 1997; Kubota et al. 2001). Thus, the inner disk radius is often related to the innermost stable circular orbit (ISCO) which in turn can be related to the black hole mass.

However, as the luminosity of the system approaches its Eddington luminosity, it starts to depart from the $L \propto T_{\text{eff}}^4$-track. Some systems, indeed, have shown that they start to follow a new flatter track of $L \propto T_{\text{in}}^4$ (Kubota and Makishima 2004), which satisfies the slim disk prediction for a non-rotating black hole.

Figure 10 shows the X-ray HR diagram of our sample. Here we use $T_{\text{in}}$ instead of $T_{\text{eff}}$, but as long as we consider a constant spectral hardening factor, $\kappa$, $T_{\text{in}} \propto T_{\text{eff}}$. The y-axis of the upper panel shows the total luminosity ($L$), obtained by summing the luminosity of the disk component ($L_{\text{disk}}$) and thermal Comptonization component ($L_{\text{THC}}$), normalized by the Eddington luminosity. The lower panel shows the disk luminosity normalized by the Eddington luminosity. The disk luminosity is calculated from the unabsorbed flux of MCD component between 0.01 – 100 keV assuming a disk geometry, a distance of 12.5 kpc, and an inclination angle of 70°. We assume an isotropic emission when we calculate the thermal Comptonization luminosity (also shown in table 3). The filled stars show data with > 50% disk fraction in their spectra, while open squares represent the data with lower disk fraction (<50%). Data with $L_{\text{disk}} < 0.02L_E$ are not shown in the lower panel for clarity.

It is not always clear which luminosity ($L$ or $L_{\text{disk}}$) is better for this kind of plot. In the present study we plot both luminosities for completeness. In disk-dominated data, the disk fraction is moderately higher than that of the thermal Comptonization component and thus both luminosities give similar results. By contrast, for Comptonization-dominated data, their position in the X-ray HR diagram depends on the choice of luminosity, $L$ or $L_{\text{disk}}$ (compare upper and lower panels of figure 10). As shown in the upper panel, these data have comparable total luminosities to those of disk-dominated data. However, their disk fraction is mostly low and thus their position is shifted to a lower position in the lower panel of figure 10. Data with a very low disk fraction ($\sim 0$) do not follow the $L \propto T_{\text{in}}^4$-track in the lower panel. Moreover, the disk temperature value obtained from fitting becomes less reliable since the disk contribution is almost negligible (see section 4.1.1).

From the lower panel of figure 10, we can see that there are two groups of data following two different $L_d \propto T_{\text{in}}^4$-tracks. The upper branch seems to extend to the lower disk luminosity data (open squares) but these data are those whose spectra are dominated by the thermal Comptonization. All spectra of the data in the lower branch are disk-dominated and their disk luminosity is below 0.5$L_E$. The lower branch may correspond to the highest end of standard accretion disk branch in the high/soft state or slim-disk state (see below).

In figure 10, we also plot some lines from equation [9] of Makishima et al. (2000), assuming $L_E = 1.5 \times 10^{38}(M/M_\odot)$ erg s$^{-1}$. It is assumed that the inner edge of the disk reaches the ISCO, $r_{\text{in}} = 3r_S$ for a non-rotating black hole and $r_{\text{in}} = 0.5r_S$ for a maximally rotating black hole. Given that we know the black hole mass from dynamical methods, $M = 14M_\odot$, we can plot the lines for different values of $\kappa$, by assuming a value of black hole spin. In figure 10, we assume a black hole spin of 0 (non-rotating black hole). These lines of constant $\kappa$ coincide with $L \propto T_{\text{in}}^4$-tracks. The upper and lower branches, in the lower panel of figure 10, coincide with $\kappa \sim 3$ and 4 for a non-rotating black hole, respectively.

Figure 11 shows the X-ray HR diagram for both MCD (blue points) and extended DBB fits (red points). The blue open squares and filled stars are Comptonization-dominated and disk-dominated data, respectively. Red
filled circles are those datasets with \( p < 0.7 \) from extended DBB fits, while red open circles are those with \( p \sim 0.75 \). We also plot the fitting results of two datasets from numerical simulations of the slim disk model around a rotating black hole (Sadowski 2009) in blue open diamonds. The higher temperature data corresponds to a black hole spin larger than 0.99 while the lower temperature data to a black hole spin of 0.52. Relativistic effects are also included when calculating the spectrum and the spectral hardening factor is 1.7 (Sadowski et al. 2009). We draw lines that cross each simulation data point (see text).

It turns out that the dependence of \( L \) on \( T_{in} \) becomes less uncertain because of the limited range of \( T_{in} \). Caution needs to be taken, however, since the luminosity calculation from the observed flux for the extended DBB model is less reliable than that of the MCD model because the disk state is expected to become the standard one and hence \( p \) should change to 0.75 at outer radii. Rather, we can directly compare our MCD fit results (blue points) with the same plot obtained from other BHBs (e.g. Figure 5 of Kubota and Makishima 2004), where the \( L \propto T_{in}^4 \)-track is suggested at the highest temperature end based on the MCD model.

5. Discussion

GRS 1915+105 is known to be the only source in our Galaxy that persistently shines at above 10% of its Eddington luminosity. It raises a doubt on whether we ever observed the canonical high/soft state even when the disk fraction is large. We also found a puzzling behavior from our present study. In this section we will discuss our interpretation as well as explore the available scenarios for this puzzling behavior at near-Eddington luminosity.

5.1. Accretion Disk States

As shown in figure 7, there is a clear dependence of the MCD fitting components, i.e. \( r_{in} \) and \( kT_{in} \) on the disk fraction. As the disk fraction increases from 0 to 50%, the innermost temperature of the disk increases as the radius decreases. It is also shown that \( r_{in} \) remains almost constant for those datasets with disk fraction larger than 50%.

We suggest that the Comptonization-dominated spectra most probably correspond to the (strong) very high state (VHS) found in other BHBs, because of the similarity in: (1) the parameters of Comptonization \( (kT_e \sim 10–20 \text{ keV and } \tau_e \sim 2–3) \), (2) the high \( L/L_E \) value, (3) the (apparently) large \( r_{in} \) (or high \( L \)) for the given \( T_{in} \), and (4) the presence of strong (low frequency) QPOs (e.g. Morgan et al. 1997; Rodriguez et al. 2004). These are exactly found in the strong VHS of XTE J1550–564, although the real innermost radius may be smaller if the disk-corona coupling is taken into account (Done and Kubota 2006). This VHS occurs when the mass accretion rate becomes even higher than that of the high/soft state. Theoretically, some outflow material blown off the disk due to the increase of radiation pressure caused by the increase of mass accretion rate is also predicted in this state. It is very unlikely that the Comptonization-dominated spectra correspond to the canonical low/hard state of BHBs, which is normally observed at luminosities much lower than 10% of the Eddington luminosity, unlike our case. In addition, the electron temperature of the Comptonizing corona in the low/hard state (e.g. Makishima et al. 2008) is much higher (~100 keV) than those found here.

We propose that the following three branches (states) have been observed in our data sample:

1. Comptonization-dominated spectra (when the disk flux < 30% of the total flux), which correspond to the strong VHS in other BHBs.
2. Disk-dominated spectra:
   (a) Lower luminosity branch: the high/soft state, or probably the slim disk state, around a rotating black hole (see next subsection).
   (b) Higher luminosity branch: probably a truncated disk with low temperature (< 10 keV) and optically thick Comptonization. This would correspond to the new state that appears.
at luminosity very close to the Eddington luminosity. It may be understood as the extension of the high electron temperature VHS (state 1 above) when luminosity becomes higher.

State (1) and (2a) have already been observed in other BHBs, but state (2b) looks unique in GRS 1915+105, probably due to its high $BHBs$, but state (2b) looks unique in GRS 1915+105, and not the other way around. If, however, we have a moderately geometrically thick disk (slim disk) together with an outflow, there may be some interaction between the disk and the outflow and complicate the radiation track. The material outflow from the disk is a delicate process which far from being understood. We need a numerical calculation of disk-corona system with an outflow for further analysis. Kawashima et al. (2009) performed two dimensional radiation hydrodynamic simulations of supercritical accretion flows with outflows. They found a possible new state above the slim disk state in which both disk and outflow components become important. The slim disk and outflow model seems to be applicable in a particular case of ULXs (Gladstone et al. 2009).

High inner disk temperatures found in our study may be explained by a slim disk around a non-rotating black hole (e.g. Watarai et al. 2000), a standard disk around a rotating black hole (e.g. Zhang et al. 1997), or a slim disk around a rotating black hole (e.g. Sadowski 2009). As mentioned above, the non existence of $L \propto T^4_{in}$-track and the too high $\kappa$ value contradict the theoretical prediction of the slim disk around a non-rotating black hole. While the rotating black hole is a good explanation for the high inner disk temperatures (since the inner disk radius becomes closer to the black hole), the luminosities of our sample are too high to keep the disk in the standard accretion mode.

On the other hand, a clear deviation from the standard accretion disk spectra during the high/soft state as luminosity approaches the Eddington luminosity is in a good agreement with slim disk prediction. Slim disk around a rotating black hole is one plausible idea to resolve the above issues since the $L \propto T^2_{in}$-track is not necessarily held for the following reason.

In the case of a disk around a non-rotating black hole, there is a gap between the radius of the ISCO (i.e., $3r_S$) and that of the event horizon ($r_S$). As the mass accretion rate increases, the flow density inside the ISCO increases and eventually fills the gap, emitting significant radiation. Hence, substantial radiation will be emitted from there at luminosities near the Eddington. This results in a substantial decrease of the inner edge of the disk and increase of the innermost disk temperature with an increase of the mass accretion rate (and luminosity), in the way that $r_{in} \propto T^{-1}_{in}$. This leads to the relation, $L \propto r_{in}^2 T_{in}^4 \propto T_{in}^2$ (Watarai et al. 2000). This cannot happen for a maximally rotating black hole, since the ISCO is located near the event horizon, regardless of the mass accretion rate. Hence, the relation, $L \propto T^2_{in}$ will never appear.

Furthermore, if we assume a rapidly rotating black hole,
we do not need to adopt too high spectral hardening factor for the data in the lower branch of figure 11 (lower panel). Provided that the spin parameter does not change, the nature of the upper branch remains unclear. One possible explanation is the change of spectral hardening factor despite the unknown mechanism. Another possible explanation is the effect of the strong Comptonization. The inner disk is truncated and turns into Comptonizing corona, which is suggested as a picture of the VHS of normal BHBs, and thus we observed lower inner disk temperature than expected from high/soft state at the same luminosity (Done and Kubota 2006).

The fact that the upper branch in our study has never been observed in other Galactic microquasar, such as XTE J1550–564 and GRO J1655–40 (e.g. Kubota et al. 2001; 2004), may have something to do with the spin parameter. Both XTE J1550–564 and GRO J1655–40 are suggested to have a moderate spin parameter < 0.8 (e.g. Gierliński et al. 2001; Davis et al. 2006; Shafee et al. 2006). Caution needs to be taken since there are several methods in determining spin parameter which can lead to contradicting results. In the case of GRO J1655–40, for example, Reis et al. (2009) obtained a lower limit for the spin of 0.9 by using the reflection component in the spectrum. At present, there is no consensus on the best methods to determine the black hole spin parameter. Despite the fact that our present study does not focus on the determination of the spin parameter, our results suggest a rapidly rotating black hole for GRS 1915+105.

McClintock et al. (2006) find a spin parameter > 0.98 for GRS 1915+105 from their analysis. They also find that the spin decreases as the luminosity increases. They, however, choose only data with \( L_d < 30\% L_E \) to determine the spin parameter. The spin parameters obtained from data with \( L_d > 40\% L_E \), are indeed in agreement with the moderate spin parameter obtained by Middleton et al. (2006), spin parameter \( \sim 0.7 \). Middleton et al. (2006), however, due to their selection criteria, have only a restricted data sample which contains only high luminosity data, \( L_d > 40\% L_E \). Comparing the disk luminosities and temperatures obtained from both Middleton et al. (2006) and McClintock et al. (2006), data of Middleton et al. (2006) seem to correspond to our higher branch, while those of McClintock et al. (2006) with \( L_d < 30\% L_E \) correspond to the lower branch in our X-ray HR diagram.

6. Conclusions

We analyzed the spectra of GRS 1915+105 during its quasi-steady states to study the supercritical accretion processes. We found new interesting features as follows:

1. There is a strong dependence of the inner disk temperature and radius on the fraction of the disk component: the disk temperature increases as the disk fraction increases, while the opposite trend is found for the inner disk radius. The electron temperature tends to be higher when the disk fraction is small while the spectral slope remains more or less constant.

2. We also fit the data with the extended DBB model to see any deviation from the standard spectral shape. Despite the fact that the \( p \)-value deviates from the standard value \( p = 0.75 \) for data with \( L > 0.3 L_E \), the \( L \propto T_{\rm e}^2 \)-track predicted by the slim disk theory for a non-rotating black hole does not appear. A rapid spin of the black hole in GRS 1915+105 can explain these features as well as a high value of spectral hardening factor (\( \sim 4 \)) that would be required for a non-rotating black hole.

3. We observed three spectral branches (states) in our data sample: one Comptonization-dominated branch and two disk-dominated branches. We suggest that Comptonization-dominated spectra correspond to the canonical VHS observed in normal BHBs. The lower luminosity branch of disk-dominated spectra seems to correspond to the highest end of the high/soft state or the slim disk state around a rotating black hole. The higher luminosity branch of disk-dominated spectra may be interpreted as a truncated disk with low temperature and optically thick Comptonization, unique to GRS 1915+105 at near Eddington luminosity.

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