SUZAKU OBSERVATION OF GRS 1915+105: EVOLUTION OF ACCRETION DISK STRUCTURE DURING LIMIT-CYCLE OSCILLATION

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Abstract

We present results from the Suzaku observation of the microquasar GRS 1915+105 performed during the 2005 October multiwavelength campaign. The data include both stable state (class $\chi$) and limit-cycle oscillation (class $\theta$). Correct interstellar absorption as well as effects of dust scattering are fully taken into account in the spectral analysis. The energy spectra in the 2–120 keV band in both states are all dominated by strong Comptonization of disk photons by optically thick ($\tau \approx 7–10$) and low-temperature ($T_c \approx 2–3$ keV) hybrid plasmas containing non-thermal electrons produced with $10%$–$60%$ of the total power input. Absorption lines of highly ionized Fe ions detected during the oscillation indicate that a strong disk wind is developed. The ionization stage of the wind correlates with the X-ray flux, supporting the photoionization origin. The iron-K emission line shows a strong variability during the oscillation; the reflection is strongest during the dip but disappears during the flare. We interpret this as evidence for “self-shielding” that the Comptonizing corona becomes geometrically thick in the flare phase, preventing photons from irradiating the outer disk. The low-temperature and high-luminosity disk emission suggests that the disk structure is similar to that in the very high state of canonical black hole binaries. The spectral variability during the oscillation is explained by the change of the disk geometry and of the physical parameters of Comptonizing corona, particularly the fractional power supplied to the acceleration of non-thermal particles.

Key words: accretion, accretion disks – stars: individual (GRS 1915+105) – techniques: spectroscopic – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

GRS 1915+105 is the brightest microquasar in our Galaxy, providing us with a unique opportunity to study the accretion flow onto a black hole at high fractions of Eddington ratio (for a review, see Fender & Belloni 2004). This source, discovered in 1992 with the WATCH instrument on GRANAT (Castro-Tirado et al. 1992), has been persistently active up to now unlike usual soft X-ray transients. GRS 1915+105 was recognized to be a superluminal source by Very Long Baseline Array observations of radio outbursts (Mirabel & Rodríguez 1994), making it a target of great importance for studying the formation mechanism of relativistic jets. From the kinetics of the radio jets, their intrinsic speed and inclination are determined to be $0.92c$–$0.98c$ (where $c$ is the speed of light) and $66°$–$70°$, respectively (Mirabel & Rodríguez 1994; Fender et al. 1999). The near-infrared observations have revealed that the system consists of a black hole with a mass of $14\pm 4\ M_\odot$ and a K III type companion star with an orbital period of 33.5 days (Greiner et al. 2001). This indicates a huge size of the accretion disk with a continuously high mass transfer rate from the companion, which may account for many unique features of this source compared with normal black hole binary systems.

The source has been intensively studied at high energies by many observatories on different occasions. RXTE/Proportional Counter Array (PCA) observations revealed that GRS 1915+105 often exhibits dramatic temporal and spectral variations, so-called limit-cycle oscillations, unique features in accreting stellar mass black holes in our Galaxy (e.g., Belloni et al. 1997a). Belloni et al. (2000) found that the instantaneous spectral state of GRS 1915+105 can be divided into three states: States A, B, and C, where the source undergoes frequent transition or stays stable. Based on these transition patterns, they classified them into 12 classes, including two “stable” classes (Class $\chi$ and $\phi$) with little variability on a timescale longer than $\sim 1$ s. This behavior is quite different from normal black holes observed in canonical states: the low/hard, intermediate (or very high), and high/soft states (Tanaka & Lewin 1995; see also Homan & Belloni 2005 and Remillard & McClintock 2006 for more recent classification). The correspondence of States A, B, and C of GRS 1915+105 to these states is not completely understood, however (Reig et al. 2003).

Theoretically, the limit-cycle oscillation can be explained by thermal instability in the inner part of the accretion disk under high mass accretion rate, triggering limit-cycle transitions between two stable branches in the surface density versus $\dot{M}$ plane: the standard disk and optically thick advection-dominated accretion flow, so-called the slim disk (Abramowicz et al. 1988). In fact, two-dimensional hydrodynamic simulations are successful to reproduce the limit-cycle behaviors of GRS 1915+105...
quantitatively (Ohsuga 2006). However, direct observations that trace the evolution of the disk structure both in the oscillation and stable states are still insufficient to be compared with model predictions, and their interpretations may be subject to large uncertainties since understanding of the origin of the X-ray emission is not fully established. Many early works relied on the spectral modeling by a multi-color disk (MCD; Mitsuda et al. 1984) model plus a power law, as applied to other black hole binaries. There is no guarantee that this model always holds to GRS 1915+105, in particular when the power-law component dominates the entire flux.

Later observational works (Zdziarski et al. 2001; Done et al. 2004; Ueda et al. 2009) have suggested that the X-ray spectra of GRS 1915+105 at least in some states are dominated by an optically thick Comptonization of the disk photons off low-energy electrons, by applying physically more realistic models than the canonical MCD + power-law model. Zdziarski et al. (2001, 2005) analyzed broadband spectra observed with RXTE/PCA, HETE, and CGRO/OSSE, and found that they can be described by Comptonization from thermal/non-thermal hybrid plasmas. Such low-temperature, optically thick Comptonization may be a common characteristic in accretion flows at high Eddington fractions, which may apply to those onto supermassive black holes (Middleton et al. 2009).

Observations of local spectral features such as iron-K emission line and absorption lines give key information to reveal the structure of accretion discs. From high-resolution spectra (CCD or the HETGS instrument on Chandra) of GRS 1915+105, absorption lines from highly ionized ions have been clearly detected (Kotani et al. 2000; Lee et al. 2002; Ueda et al. 2009). This indicates the presence of strong disk wind most probably occurring at \( r \sim 10^4 r_g \) \( r_g \equiv GM/c^2 \) is the gravitational radius where \( G, M, \) and \( c \) being the gravitational constant, mass of the black hole, and light velocity, respectively), which carries a huge amount of accreting gas outward the system (Ueda et al. 2009; Neilsen & Lee 2009). On the other hand, the emission line profile gives constraints on the geometry between the continuum emitting region and reflector, most probably the accretion disk. An iron-K emission line has been detected from GRS 1915+105, whose shape and intensity seem to depend on the states (Kotani et al. 2000; Neilsen & Lee 2009). Since its equivalent width (EW) is not large (< 50 eV) in GRS 1915+105, we need both good spectral resolution and large effective area to accurately measure the profile, in particular to trace the change during oscillations.

Suzaku (Mitsuda et al. 2007), the fifth Japanese X-ray satellite, observed GRS 1915+105 on 2005 October 16–18 (UT throughout the paper) as a part of the science working group’s observation program. The large effective area with good energy resolution in the 0.2–12 keV band, together with the simultaneous coverage of the 10–600 keV band with unprecedented sensitivities, gives us the best opportunities to reveal the origins of the X-ray emission and disk structure of GRS 1915+105 both in stable and oscillation states. In our work, we refer to the latest results on the metal abundances of interstellar (plus circumstellar) gas toward GRS 1915+105 as determined by Chandra/HETGS (Ueda et al. 2009). In the analysis, we also take into account the effects by dust scattering, which have been ignored in most of previous works. We show that these are important for accurate modeling of the spectra. Section 2 describes the observation and data reduction, and Section 3 the light curves and states of GRS 1915+105 in our observations. The spectral analysis is presented in Section 4. We discuss the interpretation of our results in Section 5. The conclusions are summarized in Section 6. In our paper, we assume the distance of \( D = 12.5 \) kpc and inclination angle of \( i = 70^\circ \) unless otherwise stated. Around the epoch of our Suzaku observations, a large multiband campaign was conducted involving other space and ground observatories, whose results will be reported in a separate paper (Y. Ueda et al. 2010, in preparation). For the preliminary results of the campaign, refer to Ueda et al. (2006). The INTEGRAL light curves are published in Rodriguez et al. (2008a).

2. OBSERVATIONS AND DATA REDUCTION

Suzaku observed GRS 1915+105 from 2005 October 16 16:42 to October 18 23:16 for a net exposure of \( \approx 80 \) ks. Suzaku carries four sets of X-ray Telescope (XRT) each with a focal plane X-ray CCD camera, the X-ray Imaging Spectrometer (front-side illuminated XISs, XIS-0, XIS-2, and XIS-3; back-side illuminated XIS, XIS-1), and a non-imaging collimated instrument called the Hard X-ray Detector (HXD), which consists of the silicon \( p \)-intrinsic-\( n \) photodiodes (PIN) and scintillation counters made of gadolinium silicate crystals (Ce-doped \( \text{Gd}_2\text{Si}_2\text{O}_5 ; \text{GSO} \)). The XIS, PIN, and GSO simultaneously cover the energy bands of 0.2–12 keV, 10–60 keV, and 40–600 keV, respectively. The target was observed at the so-called XIS nominal position.

The XISs were operated in the normal clock mode with the 2 \( \times \) 2 editing mode for XIS-0, 2, and 3, and 3 \( \times \) 3 for XIS-1. To minimize pile-up (double photon events) due to the brightness of this source, the 1/8 window option was adopted for XIS-0, XIS-2, and XIS-3, which reduced the exposure time per frame from 8 s to 1 s. XIS-1 was operated with the 0.1 s burst plus 1/8 window option, although the 1/8 window option was turned off for XIS-1 before October 18 00:26, due to an accidental error in the satellite operation. We utilize XIS data taken with different modes according to the purpose of an analysis. The XIS-1 events are used to derive (1) unsaturated light curves with a resolution of 1 s (after October 18 00:26) and 8 s (before then) and (2) continuum spectra with little effects from pile-up, while we use XIS-0, 2, and 3 data to make the spectra with high photon statistics in the 5–10 keV band for detailed study of the iron-K features.

We analyze the data using the HEASoft version 6.4.1 package, utilizing the products version 2.0.6.13 processed by the pipeline processing team and calibration database (CALDB) released on 2008 December 3. For the analysis of the XIS data, we exclude events suffering from telemetry saturation, based on the GTI filters provided by the XIS team.\(^9\) We do not subtract the non-X-ray background or the cosmic X-ray background, which are negligible compared with the bright source counts. For the spectral analysis of the XIS-1 data taken with the full window mode before October 18 00:26, we subtract out-of-time events as background by utilizing events in an outer region in the same CCD chip. In the extraction of the spectra of XIS-0, 2, and 3 (i.e., without burst options), we exclude a circular region with a radius of 120 pixels around the target position to reduce the effects of pile-up events. It is known that the attitude of the Suzaku satellite exhibits an orbital variation by \( \approx 0.5 \) arcmin, causing periodic shifts of the target position in the focal plane. Hence, we check the central position of the source and define an event extraction region every 200 s.

http://www-cr.scphys.kyoto-u.ac.jp/member/hiroya/xis/gtifile.html
3. LIGHT CURVES AND X-RAY STATES

Figure 1 shows the light curves of GRS 1915+105 obtained with XIS-1 in the 1–10 keV band and with the HXD/PIN in the 10–60 keV during the whole observation epoch. All photons observed in the XIS-1 chip are utilized here, but the XIS-1 count rates before October 18 00:26 are artificially reduced by a factor of 0.51 to correct for the difference of the integration area from the data taken with the 1/15 window option. For convenience, hereafter we define $t$ as the time since 2005 October 16.0 in units of hours. It is seen that at $t \lesssim 40$ GRS 1915+105 was in an X-ray stable state, except for a possible flare-like event seen at $t \simeq 21.5$. From $t \simeq 40$, the X-ray flux increased rapidly and entered into “oscillation” that lasted till $t \simeq 56$. From $t \simeq 66$, GRS 1915+105 exhibits a similar X-ray flare, followed by oscillation whose variability pattern is different from the previous one (see Ueda et al. 2006 and Rodriguez et al. 2008a for X-ray light curves observed with other satellites).

Throughout the observation, the source was very bright in soft X rays, $\sim (1-3) \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band.

For comparison with previous studies of GRS 1915+105, we first identify the “Class” and “State” of GRS 1915+105 in our observations, according to the model-independent classification scheme by Belloni et al. (2000). As seen from Figure 1, GRS 1915+105 continuously stayed in the “stable state” in the period of $t = 26–38$, which is similar to the plateau state (Foster et al. 1996), before entering into the oscillation phase. Timing and spectral analyses of the data taken with the PCAs on RXTE at the epoch of $t = 23–26$ reveal that our “stable state” corresponds to Class $\chi$ (stable State C) having an extremely soft spectrum, accompanied with a quasi-periodic oscillation (QPO) at $\approx 6$ Hz (Ueda et al. 2006).

Figure 2 shows representative X-ray light curves ($t = 51.6–52.3$) in the oscillation phase taken with the Suzaku XIS-1 and PIN in the 1–10 keV and 10–60 keV bands, respectively, together with their hardness ratio. We identify the X-ray variability pattern as Class $\theta$ in Belloni et al. (2000), where the transition occurs between State C and State A (soft dip) on a timescale of $\sim 10$ minutes. It is seen that during oscillations the spectral colors significantly soften in the dip phase, as expected according to previous studies with RXTE (Belloni et al. 2000).

4. SPECTRAL ANALYSIS

4.1. Overview

For spectral analysis, we define four different states: (1) “stable state” (Stable), (2) “oscillation-high state” (Osc-H), (3) “oscillation-medium state” (Osc-M), and (4) “oscillation-low state” (Osc-L), according to time variability pattern and intensity level. The stable and oscillation-high states consist of State C data defined by Belloni et al. (2000), while oscillation-med and -low correspond to State A. The time region is taken between $t = 26.03–37.88$ for (a), when the source flux was almost constant (Class $\chi$), and $t = 45.18–53.97$ for the rest (Class $\theta$). The oscillation-high, -med, -low states are defined as when the 10–60 keV PIN count rate is above 24 counts s$^{-1}$, between 12 and 24 counts s$^{-1}$, and between 1 and 12 counts s$^{-1}$, respectively, within the above time region. The count rate thresholds for the
Figure 2. Blow up of XIS-1 (1–10 keV) and PIN (10–60 keV) light curves at $t = 51.6$–52.3 and their hardness ratio with 4 s bin. The two horizontal lines indicate the limits between the oscillation low/med and med/high states, respectively.

Table 1

| State  | Start (UT) | End (UT) | Criteria PIN (10–60 keV) | Exposure (ks) |
|--------|------------|----------|--------------------------|---------------|
| Stable | 2005 Oct 17 02:02 | 2005 Oct 17 13:53 | ... | 19.8 |
| Osc-H  | 2005 Oct 17 21:11 | 2005 Oct 18 05:58 | $>24$ counts s$^{-1}$ | 7.2 |
| Osc-M  | 2005 Oct 17 21:11 | 2005 Oct 18 05:58 | 12–24 counts s$^{-1}$ | 0.93 |
| Osc-L  | 2005 Oct 17 21:11 | 2005 Oct 18 05:58 | 1–12 counts s$^{-1}$ | 2.6 |

The spectral analysis we perform consists of two steps: (1) analysis of local features in the 5–10 keV band, which determines the parameters of a reflection component (see below) and (2) that of continuum emission over the 2–120 (or 2–50) keV band. As mentioned above, different XIS sensors are used for each purpose. For the former step, we use XIS-0, 2, and 3 (FI-XISs), which were operated without the burst options, by excluding the central core of the point-spread functions; this makes us achieve good photon statistics by avoiding extreme pile-up effects. The spectra of the three sensors are summed together with the energy responses. For the latter step, we make a simultaneous spectral fit to the spectra of XIS-1 (BI-XIS), PIN, and GSO, covering the 2–120 keV band, for the stable and oscillation-high states, while we only use the XIS-1 and PIN spectra in the 2–50 keV band for the oscillation-med and -low states, since the GSO data in these states have limited statistics due to the low flux and short exposure. The data of XIS-1, operated with the 0.1 s burst option, is almost free from pile-up effects and we can utilize all photons in the point-spread function. Thanks to this fact, we can best estimate the continuum below 10 keV with least uncertainties in the calibration of the energy response of the XIS+XRT system, although the photon statistics is poorer than the data of the three FI-XISs. The observed spectra of the XIS-1 and HXD in the stable and oscillation states are plotted in Figures 3(a) and (b), respectively.

Since the determination of the local features affects that of the continuum and vice versa, the above two steps are repeated in an iterative way. First, we roughly determine the continuum shape from the BI-XIS and HXD spectra. Second, using the FI-XISs spectra in the 5–10 keV band, we determine local iron-K features, including absorption lines and an iron-K emission line, which is modeled by a feature from a reflection component. In this stage, we fix the parameters of the continuum at the best fit obtained above except for its normalization. To take into account a remaining component of pile-up events, we add a power-law component having a positive photon index in the model, whose parameters are set free. Third, we again perform the continuum fit of the BI-XIS and HXD spectra, but including the reflection component and absorption line features, whose parameters are
fixed at the best-fit values as determined in the previous fit of the FI-XISs spectra. Detailed description of the continuum model and local features is given in the following subsections.

4.2. Absorption and Dust Scattering

In our study, special care is paid on two important effects that could affect the modeling of the continuum: (1) interstellar absorption and (2) dust scattering. It is well known that the elemental abundances in interstellar medium in our Galaxy are different by location, and are not “solar,” as often assumed in spectral analyses of Galactic sources. To model the total photoelectric absorption toward GRS 1915+105, we refer to the results by Ueda et al. (2009) obtained from the Chandra/HETGS spectrum, in terms of “equivalent” hydrogen column densities (converted from the solar abundances by Anders & Grevesse 1989) of $2.78 \times 10^{22}$ cm$^{-2}$ for H, He, C, N, and O, $6.3 \times 10^{22}$ cm$^{-2}$ for Ne, Na, Mg, and Al, $5.8 \times 10^{22}$ cm$^{-2}$ for Si, $7.6 \times 10^{22}$ cm$^{-2}$ for S, Cl, Ar, and Ca, and $10 \times 10^{22}$ cm$^{-2}$ for Cr, Fe, Co, and Ni. The absorption cross section by Wilms et al. (2000) is adopted, which is available as TBvarhabs model in XSPEC.

We also take into account the effects by dust scattering, which are more significant in soft X-rays particularly below $\sim 3$ keV. A part of direct emission from a heavy absorbed source is scattered out by interstellar dust in the line of sight, while photons emitted with slightly different angles are scattered in, thus making dust-scattering halo around the target. At first-order approximation the scattered-in and scattered-out lights cancel each other, although there is time delay before scattered-in components reach an observer following the direct component. Hence, we do need to correct for this effect as far as the source spectrum is constant and one can integrate all the emission including both direct and halo components.

This is not the case for GRS 1915+105 observed with Suzaku, however, because (1) the halo components cannot be fully collected in a limited field of view of the XIS and (2) the source is highly variable in the oscillation states. Assuming the same image profile of the dust-scattered halo as GX 13+1 (Smith et al. 2002), which has a similar absorption column density to GRS 1915+105, we find that the effective area of the XIS-1 (full window) for the halo component is $\approx 60\%$ of that for the direct (i.e., point source) one, and thus the scattering effect is not canceled out even when the spectrum is constant. When it is variable, the situation becomes more complex; the total spectrum observed in a given time interval is contaminated by halo components emitted in earlier epochs due to their time delay. The timescale of the delay is estimated to be $\sim \theta^2 D/c$, where $\theta$ and $D$ are the halo size and distance to the source, respectively. Taking $\theta \sim 2'$ according to the halo profile of GX 13+1, we estimate the delay to be $\sim 100$ hr, much longer than the timescale of the oscillations. This means that we approximately observe the spectrum of variable direct emission plus constant dust-scattered component in the oscillation states. According to the light curve of all-sky monitor on RXTE (Ueda et al. 2006), the averaged flux level was almost constant for $\sim 15$ days before our observation epoch, and thus we can reasonably assume that the shape of the direct spectrum producing the observed halo component is the same as that of the stable state.

To make the best estimate of the continuum spectra including low energies below $\sim 3$ keV, we derive the spectrum of the halo component in the stable state, by taking into account the fact that $60\%$ of the scattered-in component is contained in the observed spectrum. Here we refer to the cross section of dust scattering given by Draine (2003), which is fine-tuned to reproduce the observed halo intensity of GX 13+1 (Smith et al. 2002) at its hydrogen column density (Ueda et al. 2005). For the oscillation states, we subtract this component from the observed spectra and fit them by considering the opacity of both dust-scattering and photoelectric absorption. We assume that the halo component is the same as in the stable state and is constant during the oscillation. The dust-scattered component is plotted in Figures 3(a) and (b). Its fraction in the direct (unscattered) component is found to be 6%, 7%, and 15% at 3 keV in the oscillation-high, -med, and -low states, respectively, which increases toward lower energies approximately as $\propto E^{-2}$.

4.3. Iron-K Features

The spectra of the FI-XISs with rich photon statistics reveal that the iron-K features are different between the four states.
Figure 4 shows the summed FI-XISs spectra in the 5–10 keV band. The solid curves (red) represent the best-fit continuum model from which an iron-K emission and absorption lines are excluded. The lower panel plots the residuals in units of ratio between the data and above model. From left to right and top to bottom: (a) stable, (b) oscillation-high, (c) oscillation-med, and (d) oscillation-low state.

(A color version of this figure is available in the online journal.)

Figure 4 shows the summed FI-XISs spectra in the 5–10 keV band from which the estimated pile-up components (see above) are subtracted. The overlaid model is the best-fit continuum model with its reflection component, described below, from which both iron-K emission and absorption lines are excluded to show their significance; the ratio of the data to the model is plotted in the lower panel. In addition to a deep absorption edge at 7.11 keV due to the overabundance of iron in the interstellar or circumstellar medium toward GRS 1915+105, we detect an emission line centered at 6.5–6.6 keV in both stable and oscillation-low states, whereas it is very weak in the oscillation-high and -medium states. We also find a strong absorption line feature from He-like and H-like iron ions at ≃6.6 and ≃7.0 keV in the oscillation-low state, which is weaker in the other states; in particular, no significant absorption lines are detected in the stable state.

We model the iron-K emission line by utilizing the pexriv reflection code (Magdziarz & Zdziarski 1995), which calculates both reflection continuum and fluorescence line. The line profile is further blurred with the diskline kernel (Fabian et al. 1989), by assuming that it originates from the accretion disk between the radii $r_{in}$ and $r_{out}$ with an emissivity law of $r^{\beta}$. The free parameters are (1) the solid angle of the reflector $\Omega$, which basically determines the EW of the emission line, (2) ionization parameter $\xi \equiv L/nr^2$ (Tarter et al. 1969; where $L$, $n$, and $r$ are the luminosity, density of the reflector, and distance from the emitter, respectively), and (3) innermost radius $r_{in}$. We fix an iron abundance at the same value as in the interstellar absorption,
an inclination of 70°, β = −3, and $r_{\text{out}} = 10^5 r_g$. Note that the pexriv model does not properly calculate the additional broadening by Comptonization in the emission line profile (see Ballantyne et al. 2001). Thus, we may slightly underestimate the true EW, and hence the reflection strength in the stable state, where the ionization parameter is found to be $\log \xi = 2$–3. In the oscillation states, the effects are expected to be negligible due to the low ionization parameter ($\log \xi \lesssim 2$). The absorption lines are modeled by Gaussians with a $1\sigma$ width fixed at 12 eV. The best-fit parameters are summarized in Table 2.

### 4.4. Continuum Model

The overall shape of the continuum in the four states is characterized by a steep power law with a photon index of $\approx 3$ at ~5–50 keV. To find an appropriate model to describe the continuum, we begin with fitting the XIS + HXD spectra in the 2–120 keV in the stable state, by taking into account the interstellar absorption and dust scattering described in Section 4.2, and the reflection component whose parameters are determined in the previous subsection. In addition, to include the opacity of the highly ionized gas responsible for the iron-K absorption lines, we introduce absorption edges at $\approx 8.6$ keV and $\approx 9.0$ keV corresponding to those by Fe XXV and Fe XXVI ions, respectively. We fix the optical depth according to the EW of the corresponding absorption line (see line Table 2), based on the results by Ueda et al. (2009).

We first apply a canonical model consisting of an MCD component and a power law, which turns out to not acceptable ($\chi^2$/dof = 559/354); moreover, the best-fit results are quite unphysical because (1) the innermost temperature of the MCD model is high ($\approx 3$ keV) with an extreme small radius ($\approx 4$ km) and (2) the power-law component dominates the flux over the entire band. This confirms that the spectral state is very different from the canonical high/soft state of black hole binaries. Similar fitting results are reported by Muno et al. (1999) from RXTE/PCA data of GRS 1915+105 when the 0.5–10 Hz QPOs are observed.

Next, we apply a thermal Comptonization model by Życki et al. (1999) with seed photons from an MCD component, as adopted by Done et al. (2004), Ueda et al. (2009), and Vierdayanti et al. (2009). By considering that a part of the MCD photons can escape without being Comptonized, the model is expressed as $\text{thComp} + \text{diskbb}$ in the XSPEC terminology. The innermost temperature of seed photons input to the $\text{thComp}$ model and that of the MCD component are tied to each other. We find that, while it gives a reasonable fit to the data below ~50 keV, a significant excess remains above this energy, indicating the presence of a non-thermal tail as discovered with OSSE (Zdziarski et al. 2001) and INTEGRAL (Rodríguez et al. 2008b).

Accordingly, by adding a power-law component (and its reflection) to the above model, we obtain an acceptable fit ($\chi^2$/dof = 344/350) from the broadband spectra in the stable state. This result indicates that the spectrum can basically be represented with Comptonization of disk photons both by thermal and non-thermal electrons. The power-law description of non-thermal Comptonization is unphysical, however, since it must breaks at energies of seed photons in reality.

As a more physically self-consistent model of Comptonization, we finally adopt the eqpair model developed by Coppi (1999), instead of $\text{thComp}$. It was adopted by Zdziarski et al. (2001, 2005) to fit the RXTE and OSSE spectra of GRS 1915+105 in Classes $\chi$, $\gamma$, and $\omega$ successfully. This model computes Comptonization from a hybrid plasma consisting of thermal and non-thermal electrons, where the physical processes are self-consistently solved with an energy input of accelerated electrons in a background thermal plasma. The model parameters are (1) the optical depth for scattering $\tau$, (2) compactness parameters, defined as $l_h \equiv L_h \sigma_T/(R m_e c^3)$, where $L_h$ is the power supplied to the plasma and that in seed photons, $\sigma_T$ is the Thomson cross section, $R$ is the the plasma size, and $m_e$ is the electron mass, and (3) its ratio between non-thermal and thermal electrons, $I_{\text{th}}/I_{\text{th}}$, where $I_h \equiv I_{\text{th}} + I_{\text{nt}}$. The injected non-thermal electrons have a power-law energy distribution between the Lorentz factors $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ with an index of $\Gamma_{\text{inj}}$. In the spectral fitting, we fix $l_h \equiv 1000$, $\gamma_{\text{min}} \equiv 1.3$, and $\gamma_{\text{max}} \equiv 1000$. In this model, the energy balance between Compton and Coulomb interactions determines the temperature of thermal electrons, which is automatically calculated from the given parameters.

We find that the $\text{eqpair} + \text{diskbb}$ model, with the reflection of the former component, provides an excellent description of the continuum in all four states. The direct MCD component is required in the stable and oscillation-high states with the F-test probability of $7 \times 10^{-3}$ and $3 \times 10^{-3}$, respectively. Although it is not significant in the oscillation-med and -low states, we include this component for consistency. Figure 5 plots the unfolded spectra in units of $E(\gamma)$, where $I(\gamma)$ is the energy flux. The Comptonized component, MCD model, and the reflection component including the iron-K emission line are separately plotted. The best-fit continuum parameters are summarized in Table 2, together with the observed 2–10 keV and 10–50 keV fluxes and absorption-corrected 0.01–100 keV luminosities for the Comptonization and MCD component, where a spherical and disk geometry is assumed, respectively. For the oscillation-med and -low states, we fix $\Gamma_{\text{inj}} = 3.1$, the best-fit value obtained in the oscillation-high state, since it is difficult to constrain the slope without the coverage above 50 keV in these states.

### 5. DISCUSSION

#### 5.1. Results Summary

With Suzaku, we obtained high-quality broadband X-ray spectra of GRS 1915+105 over the 2–120 keV band both in the stable (Class $\chi$) and oscillation states (Class $\theta$), covered with CCD energy resolution (FWHM ~ 120 eV at 6 keV) below 10 keV. The best estimated interstellar absorption and dust scattering effects are taken into account in the spectral fitting, which have been ignored in most previous studies of GRS 1915+105. In particular, we caution that without correct modeling of the absorption with over iron abundances, one can easily reach wrong conclusions on the iron-K emission line profile that requires very careful analysis of the continuum shape. The best-fit models in units of $E(\gamma)$, corrected for the interstellar absorption and scattering, are plotted in Figure 6 for the four states. Below, we interpret our results based on the iron-K features and continuum model. We find that the iron-K features in the oscillation-low state are very similar to those in the “soft state” (steady State A) of GRS 1915+105 detected by Ueda et al. (2009) using Chandra/HETGS. This may be expected, since our oscillation-low state mostly corresponds to State A, though not in a steady state.

#### 5.2. Change of Reflection

We detect significant iron-K emission lines, direct evidence for the reflection, in the stable, oscillation-med, and oscillation-low states. The line profiles indicate that the reflector is
### Table 2

#### Spectral Parameters

| Parameters | Stable | Osc-H | Osc-M | Osc-L |
|------------|--------|-------|-------|-------|
| Column Densities\(^a\) (N\(_i\)) | | | | |
| H (10\(^{22}\) cm\(^{-2}\)) | | | | |
| Mg (10\(^{22}\) cm\(^{-2}\)) | | | | |
| Si (10\(^{22}\) cm\(^{-2}\)) | | | | |
| S (10\(^{22}\) cm\(^{-2}\)) | | | | |
| Fe (10\(^{22}\) cm\(^{-2}\)) | | | | |

| Continuum\(^b\) | | | | |
| \(T_k\) (keV) | 0.53 ± 0.04 | 0.79\(^{+0.02}_{-0.04}\) | 0.57 ± 0.16 | 0.49\(^{+0.14}_{-0.19}\) |
| \((T_k\) (keV)) | 2.2\(^{+0.2}_{-0.2}\) | 2.8\(^{+0.2}_{-0.2}\) | 1.7\(^{+0.4}_{-0.4}\) | 1.8\(^+0.3\) |
| \(l_k/l_h\) | 0.94\(^{+0.04}_{-0.02}\) | 0.84\(^{+0.02}_{-0.05}\) | 0.69\(^{+0.10}_{-0.07}\) | 0.75\(^{+0.16}_{-0.07}\) |
| \(l_{\text{in}}/l_h\) | 0.55 ± 0.02 | 0.39\(^{+0.04}_{-0.01}\) | 0.34 ± 0.09 | 0.17 ± 0.05 |
| \(\tau\) | 8.3 ± 0.3 | 7.5\(^{+0.5}_{-0.1}\) | 10\(^{-1.7}\) | 10\(^{-1.1}\) |
| \(\Gamma_{\text{inj}}\) | 3.7 ± 0.2 | 3.1 ± 0.3 | 3.1 (fixed) | 3.1 (fixed) |
| \(R_{\text{MCDD}}\) (km)\(^c\) | 300\(^+50_{-30}\) | 120\(^{+10}_{-10}\) | 100\(^{+30}_{-60}\) | 150\(^{+50}_{-150}\) |
| \(R_{\text{in}}\) (km)\(^d\) | 420\(^{+60}_{-30}\) | 210\(^{+20}_{-10}\) | 360\(^{+210}_{-130}\) | 390\(^{+380}_{-160}\) |

| Reflection\(^e\) | | | | |
| \(\Omega/(2\pi)\) | 0.11 ± 0.02 | <0.02 | 0.10 ± 0.07 | 0.54\(^{+0.06}_{-0.07}\) |
| \(l_{\text{in}}\) (\(r_g\)) | 530\(^{+60}_{-150}\) | 120 (fixed) | 100\(^{+30}_{-60}\) | 39\(^{+10}_{-10}\) |
| \(r_{\text{in}}\) (\(r_g\)) | 1000\(^{-200}_{-0}\) | 290 (fixed) | 290 (fixed) | 290\(^{+170}_{-140}\) |
| (EW)\(^f\) (eV) | 33 | <4 | 13 | 42 |

### Iron-K Absorption Features

| Parameters | Stable | Osc-H | Osc-M | Osc-L |
|------------|--------|-------|-------|-------|
| \(E_{\text{cen}}\) (keV) | | | | 6.76 ± 0.33 |
| \(E_{\text{cen}}\) (eV) | | | | 26\(^{+2}_{-5}\) |
| \(E_{\text{cen}}\) (keV) | 6.99 (fixed) | 6.99\(^{+0.02}_{-0.05}\) | 7.01 ± 0.10 | 7.02 ± 0.02 |
| \(E_{\text{cen}}\) (eV) | <0.9 | 10.1\(^{+2.7}_{-2.4}\) | 15\(^{+8}_{-9}\) | 39\(^{+9}_{-9}\) |
| \(r_{\text{edge}}\) | 0 | 0 | 0 | 0.11 |
| \(r_{\text{edge}}\) | 0 | 0.051 | 0.072 | 0.20 |

### Luminosity and Flux

| Parameters | Stable | Osc-H | Osc-M | Osc-L |
|------------|--------|-------|-------|-------|
| \(L_{\text{MCDD}}\) (10\(^{38}\) erg s\(^{-1}\)) | 9.2 | 7.6 | 3.0 | 2.8 |
| \(L_{\text{MCDD}}\) (10\(^{38}\) erg s\(^{-1}\)) | 10.4 | 15.2 | 14.4 | 8.8 |
| \(F_{\text{2–50 keV}}\) (10\(^{-8}\) erg cm\(^{-2}\) s\(^{-1}\)) | 1.69 | 2.88 | 1.92 | 1.12 |
| \(F_{\text{10–50 keV}}\) (10\(^{-8}\) erg cm\(^{-2}\) s\(^{-1}\)) | 0.63 | 1.03 | 0.39 | 0.17 |

### Fitting Information

| Energy Range (keV) | 2–120 | 2–120 | 2–50 | 2–50 |
| \(\chi^2/\text{dof}\) | 319/351 | 890/930 | 114/101 | 127/128 |

**Notes.** The errors are 90% confidence level for a single parameter.

\(^a\) Equivalent hydrogen column densities as determined by Ueda et al. (2009), in units of solar abundances (Anders & Grevesse 1989) between the element and hydrogen. The abundance ratios within each group of H–He–C–N–O, Ne–Na–Mg–Al, S–Cl–Ar–Ca, and Cr–Fe–Co–Ni are fixed at the solar values.

\(^b\) Fit with \(\text{eqpair}\) with an MCD spectrum as seed photons (see the text). The compactness parameter for the seed photons is assumed to be \(l_h = 1000\). Non-thermal electrons are considered between \(\gamma_{\text{min}} = 1.3\) and \(\gamma_{\text{max}} = 1000\) with a power-law index of \(\Gamma_{\text{inj}}\).

\(^c\) The normalization of the directly observed MCD component in terms of an innermost radius. The distance \(D = 12.5\) kpc and inclination \(i = 70^\circ\) are assumed without corrections for the color and boundary condition.

\(^d\) The innermost radius estimated from both Compton-scattered and unscattered MCD photons (see the text).

\(^e\) Compton reflection based on the code by Magdziarz & Zdziarski (1995), blurred by the \(\text{diskline}\) kernel with an emissivity law of \(r^\beta\) between the inner radius \(r_{\text{in}}\) and outer radius \(r_{\text{out}}\), where \(\beta = -3\) and \(r_{\text{out}} = 10^4r_g\). The accompanied iron-K emission is included.

\(^f\) The equivalent width of the iron-K\(\alpha\) emission line with respect to the total continuum.

\(^g\) Intrinsic luminosity of the direct continuum (without the reflection component) in the 0.1–100 keV band, corrected for absorption. A spherical geometry is assumed for the \(\text{eqpair}\) component, while a disk geometry is for the MCD component.

\(^h\) Observed flux in the 2–10 keV or 10–50 keV band.
moderately ionized ($\log \xi \sim 1–3$) and is located far away from the black hole as constrained by its “narrow” line width; it is most probably the outer parts of the accretion disk, whose inner radius is estimated to be $\gtrsim 300r_g$ by assuming an emissivity law of $r^{-3}$. This does not mean that the disk must be truncated at that location. If the scale height of the central source is smaller compared with that of the outer disk, then the emissivity law is better expressed with an index lower than 3, which would yield a much smaller inner radius. The absence of a relativistic broad iron-K line is consistent with the picture that the innermost part of the disk is covered by an optically thick hot plasma, smearing out any emission features due to strong Comptonization.

During the limit-cycle oscillation, the EW of the iron-K emission line (see Table 2) is the largest in the oscillation-low state. It decreases with X-ray flux, and the line disappears in the oscillation-high state. The change of the ionization parameter, determined by the X-ray luminosity, is expected to be within a factor of 3 during the oscillation. Hence, we must attribute this change mainly to the variability in the solid angle of the reflector as seen by the central source. In the stable state, the solid angle is small $\Omega/2\pi \approx 0.1$ as well, similar to that found in the oscillation-med state.

**Figure 5.** Unfolded spectra in units of $E_1(E)$ obtained from the XIS-1 and HXD data (red, crosses) plotted with separate contribution of the model; from upper to lower: the total (solid, green), Comptonized component (dot, blue), direct MCD component (dash, cyan), and reflection component (dot-dash, black). From left to right and top to bottom: (a) stable, (b) oscillation-high, (c) oscillation-med, and (d) oscillation-low state.

(A color version of this figure is available in the online journal.)

**Figure 6.** Best-fit models in units of $E_1(E)$ corrected for the interstellar absorption and dust scattering in the four states. From upper to lower (at 20 keV): oscillation-high (red), stable (cyan), oscillation-med (green), and oscillation-low states (blue).

(A color version of this figure is available in the online journal.)
We interpret that this is the first observational evidence for "self-shielding" effects of the inner part of the accretion disk. The dynamical structure of outer parts of the accretion disk, $r \gtrsim 300r_g$, cannot be changed on a timescale of the limit cycle, $\sim 1000$ s, much shorter than that of viscosity (Shakura & Sunyaev 1973). Therefore, the only possible mechanism that can dramatically reduce the observed reflection strength in the oscillation-high state must be related to the geometry in the central source; most of the continuum X-ray emission seen by an observer (i.e., with $i = 70^\circ$) does not reach the outer parts of the disk in this state. As we describe later, the inner accretion disk is covered by hot corona responsible for Comptonization. Our observations imply that the inner part of the disk becomes geometrically thick in the oscillation-high state, and Comptonized photons are shielded by the surrounding cool region of the expanded disk when viewed at a very high inclination angle from the outer disk. The evolution of the disk geometry is in accordance with theoretical prediction of the slim disk (Abramowicz et al. 1988) and numerical simulation (e.g., Ohsuga 2006).

5.3. Disk Wind

As has been revealed by previous studies (Kotani et al. 2000; Lee et al. 2002; Ueda et al. 2009; Neilsen & Lee 2009), absorption lines of highly ionized ions indicate the presence of a disk wind in the line of sight between the continuum emitter and the observer. The disk wind has a velocity of $v_{\text{wind}} \approx 500$ km s$^{-1}$ and is most likely launched at outer parts of the disk, $r_{\text{wind}} \sim 10^2r_g$ (Ueda et al. 2009), by irradiation from the central source. During the limit cycle, the absorption lines are the deepest in the oscillation-low state and become weaker as the hard X-ray flux increases. This strongly supports the photoionization of the wind; the corresponding ionization parameters estimated from the population ratio between Fe $xxvi$ and Fe $xxv$ are consistent with the change of the luminosity (based on an XSTAR simulation; Kallman 2003). The self-shielding is not relevant for photoionization, as the wind we observe is located 20$^\circ$ above the disk plane. The wind is most probably developed by the strong X-ray irradiation in the oscillation-low state, as indicated by its strong iron-K emission line. Once a disk wind is launched, it will travel over a timescale of $t_{\text{wind}}/v_{\text{wind}} \sim 10^3$ s, and hence we can approximate that the same disk wind steadily exists during the limit cycles.

In the stable state, we do not detect any iron-K absorption lines. This suggests three possibilities: (1) the wind is not developed, (2) the wind is fully ionized, or (3) the scale height of the disk wind is too low to be observed. We consider the first possibility unlikely because the absorption lines have been detected in the same Class $\chi$ state even when the hard X-ray flux is lower than in our observation (Lee et al. 2002). Indeed, the presence of iron-K emission line suggests that illumination of the outer parts of the disk does occur, which can trigger the launch of the wind. The second possibility cannot be ruled out, if the density of the wind is much smaller than that develops in the oscillation states. Then, the ionization parameter may become sufficiently large to be fully ionized, even if the luminosity is smaller that in the oscillation-high state. The third possibility is also plausible.

5.4. Origin of the Continuum

We have shown that the broadband spectra in all the four states can be commonly explained by Comptonization of seed disk photons off optically thick ($\tau \approx 7$–10), low-temperature ($T_s \approx 2$–3 keV), non-thermal hybrid plasmas. Similar results are obtained by Zdziarski et al. (2001) in another state of GRS 1915+105 (Class $\gamma$ or State B). These findings indicate that the optically thick and low-temperature Comptonization are common features in accretion flows at high Eddington fractions, as suggested by Done et al. (2004) and Ueda et al. (2009). In the stable and oscillation-high states, we find that the fractional power supplied to non-thermal electrons is quite large ($l_{\text{inj}}/l_{\text{th}} = 0.4$–0.6) and the slope of the electron energy distribution is steep ($\Gamma_{\text{inj}} \approx 3$–4) compared with the results reported from other data of GRS 1915+105 (Zdziarski et al. 2005). This may be related to the high luminosities in those states ($2 \times 10^{39}$ erg s$^{-1}$). Figure 7 plots the absorption-corrected $E1(E)$ spectrum in the stable state with the separate contribution from the MCD, reflection, and purely "thermal" Comptonization component that would be observed without non-thermal electrons. This illustrates the importance of non-thermal processes in these data.

With the "eqpair" modeling, we find that a direct MCD component is necessary in addition to the Comptonized emission in the stable and oscillation-high states, assuming the same temperature for the seed photons and MCD component. This implies that (Case I) the Comptonizing plasmas are patchy over the disk, or (Case II) they are located inside a "truncation radius" of the standard disk. In reality, such truncation would be smooth; the disk may gradually change into the "disk+corona" region, as suggested for the very high state of canonical black hole binaries (e.g., Done & Kubota 2006). In Case II, the assumption of the same spectrum for the direct MCD and seed photons do not hold, and a disk radius derived from such a simple model may be largely overestimated from the true disk size if the energetics coupling between the disk and corona is taken into account (Done & Kubota 2006).

From the observed flux and innermost temperature obtained from the fit, we can estimate the innermost radius of the accretion disk both for the direct MCD component ($R_{\text{in}}^{\text{MCD}}$) and that of the seed photons for the Comptonized component ($R_{\text{in}}^{\text{Comp}}$). We calculate $R_{\text{in}}^{\text{Comp}}$ by assuming the conservation of photon
numbers in the Comptonization process, according to the formula (A1) of Kubota & Makishima (2004) with the left-hand term increased by a factor of 2 for the optically thick case. The resultant values of $R_{m}^{\text{MCD}}$ and $R_{m}^{\text{total}} = \sqrt{(R_{m}^{\text{MCD}})^2 + (R_{m}^{\text{Comp}})^2}$ are listed in Table 2, without any corrections for the boundary condition and color/effective temperature, which would increase the radius by a factor of $\approx 1.2$ (Kubota et al. 1998). In Case I, $R_{m}^{\text{total}}$ corresponds to the true innermost radius corrected for the partial coverage by Comptonizing clouds.

We find evidence for the evolution of $R_{m}^{\text{total}}$ during the oscillation, which increases by $\approx 210$ km in the oscillation-high state to $\approx 400$ km in the oscillation-med/low states, although the significance of the change is marginal due to the large uncertainties in the latter states. They correspond to $\approx 10r_g$ and $\approx 20r_g$, respectively, by assuming the black hole mass of $14 M_{\odot}$. This implies that an inner disk forms as accumulated matter rapidly accretes onto the black hole in the flare phase. Such variation of the disk radius during limit-cycle oscillations has been reported based on simple MCD + power-law fitting (e.g., Belloni et al. 1997b; Migliari & Belloni 2003), although we obtain larger radii than these studies that refer only to the MCD component by ignoring Comptonized photons. In the stable state, the radius ($R_{m}^{\text{total}} \approx 420$ km) is significantly larger than that in the oscillation-high state. Thus, if Case I is true, our results suggest that the standard disk does not extend down to the innermost stable circular orbit (ISCO) regardless of the black hole spin in all our states, unlike in some cases of the “soft state” of GRS 1915+105 (McCIntoch et al. 2006; Middleton et al. 2006; Vierdayanti et al. 2009). Such low-temperature/high-luminosity disk emission that leads to an apparently large disk radius is observed in the very high state of other black hole binaries (Done & Kubota 2006), when the Eddington ratio is higher than that in the high/soft state. At even higher Eddington fractions that trigger limit cycles, as in our case, the situation may be the same as in the canonical very high state.

The Comptonization parameters also show significant change during the limit-cycle oscillation, besides the disk radius (and disk temperature) as discussed above. In the oscillation-high state, the fractional power supplied to non-thermal electrons becomes the largest ($l_{th}/l_{b} \approx 0.4$) and the electron temperature highest ($T_{e} = 2.8$ keV), which decreases to $l_{th}/l_{b} \approx 0.2$ and $T_{e} = 1.8$ keV in the oscillation-low state, respectively. Thus, in the flare phase, very efficient particle acceleration must occur by converting the gravitational energy of accreting mass. This may increase the temperature of thermal electrons and expand the size of the corona. As the corona becomes geometrically thick, the “self-shielding” effect starts to work, preventing the Comptonized photons from irradiating the outer part of the accretion disk (i.e., little reflection signals). A similar situation (geometrically thick corona) may be realized in the stable state as well, where the reflection strength is weaker compared with the oscillation-low states.

To summarize, with the simple spectra model presented above, we show that the dramatic change of X-ray flux and spectra during the limit-cycle oscillation can be explained mainly by (1) the evolution of the disk geometry and (2) that of physical parameters of Comptonizing corona, particularly the fractional power supplied to non-thermal electrons. We note, however, that the assumption of the MCD model (i.e., standard disk) in all states and that of the same temperature for the seed photons of Comptonization would be oversimplification. For instance, disk instability theories predict that a slim disk appears in the oscillation-high state (Abramowicz et al. 1988), which predicts different spectra from the MCD model. This is not ruled out from the current simple analysis. Nevertheless, we stress that the role of Comptonization becomes very important in determining the whole dynamics and energy spectra of black hole accretion disks at high mass accretion rates, which must be taken into account in any theoretical studies.

6. CONCLUSIONS

1. We find that the Suzaku broadband spectra of GRS 1915+105 band both in the stable (Class $\chi$) and oscillation states (Class $\theta$) are commonly represented with a model consisting of an MCD model and its Comptonization with a reflection component, over which the opacity of the disk wind (including iron-K absorption lines) is applied. The Comptonized component dominates the flux above $\sim 2$ keV.

2. The Comptonization is made by optically thick ($\tau \approx 7$–10), non-thermal/thermal ($T \approx 2$–3 keV) hybrid plasmas. The non-thermal electrons are produced with 10%–60% of the total energy input to the plasma with a power-law index of $\approx 3$–4, which account for the hard X-ray tail above $\sim 50$ keV.

3. During the limit-cycle oscillation, the reflection strength, estimated by the iron-K emission line, is the largest during the dip phase but disappears in the flare phase. We interpret this as evidence for self-shielding effects that Comptonized photons are obscured by the surrounding cool region of the expanded disk when viewed at a very high inclination angle from the outer disk. The variation of the disk geometry is in accordance with theoretical predictions.

4. The disk wind, traced by iron-K absorption lines of Fe $\text{xxv}$ and Fe $\text{xxvi}$, always exists during the oscillation and its ionization well correlates with the X-ray flux. This supports the photoionization origin. In the stable state, the iron-K absorption lines are not detected probably because it is highly ionized and/or the scale height is small.

5. The disk parameters suggest that the inner disk structure is similar to that in the very high state of black hole binaries. The spectral variability in the oscillation state is explained by the change of the disk geometry and of physical parameters of Comptonizing corona, particularly the fractional power supplied to the acceleration of non-thermal particles.

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