THE TRUNCATED DISK FROM SUZAKU DATA OF GX 339–4 IN THE EXTREME VERY HIGH STATE

Manami Tamura\textsuperscript{1}, Aya Kubota\textsuperscript{1}, Shinya Yamada\textsuperscript{2}, Chris Done\textsuperscript{3}, Mari Kolehmainen\textsuperscript{3}, Yoshihiro Ueda\textsuperscript{4}, and Shunsuke Torii\textsuperscript{5}

\textsuperscript{1} Department of Electronic Information Systems, Shibaura Institute of Technology, 370 Fukasaku, Minuma-ku, Saitama, Saitama 337-8570, Japan; ml10090@shibaura-it.ac.jp, aya@shibaura-it.ac.jp
\textsuperscript{2} Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
\textsuperscript{3} Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK
\textsuperscript{4} Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan
\textsuperscript{5} Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

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ABSTRACT

We report on the geometry of accretion disk and high-energy coronae in the strong Comptonization state (the very high/steep power law/hard intermediate state) based on a Suzaku observation of the famous Galactic black hole GX 339–4. These data were taken just before the peak of the 2006–2007 outburst, and the average X-ray luminosity in the 0.7–200 keV band is estimated to be $2.9 \times 10^{38}$ erg s$^{-1}$ for a distance of 8 kpc. We fit the spectrum with both simple (independent disk and corona) and sophisticated (energetically coupled disk and corona) models; all fits imply that the underlying optically thick disk is truncated significantly before the innermost stable circular orbit around the black hole. We show this directly by a comparison with similar broadband data from a disk-dominated spectrum at almost the same luminosity observed by XMM-Newton and RXTE 3 days after the Suzaku observation. During the Suzaku observation, the quasi-periodic oscillation (QPO) frequency changes from 4.3 Hz to 5.5 Hz, while the spectrum softens. The energetically coupled model gives a corresponding 5% $\pm$ 8% decrease in the derived inner radius of the disk. While this is not significant, it is consistent with the predicted change in QPO frequency from the Lense-Thirring precession of the hot flow interior to the disk and/or a deformation mode of this flow, as a higher QPO frequency implies a smaller size scale for the corona. This is consistent with the truncated disk extending further inward toward the black hole.

Key words: accretion, accretion disks -- black hole physics -- stars: individual (GX 339–4) -- X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The accretion flow in black hole binaries (BHB) is generally unstable, so most sources are transient (e.g., Lasota 2001), showing dramatic outbursts with a large change in mass accretion rate and a correspondingly large change in X-ray properties (McClintock & Remillard 2006). Generally, these start in the low/hard state (LHS) where the disk is very dim, and the spectrum is dominated by a hard Comptonized spectrum up to 100–200 keV. This brightens rapidly while remaining hard. Then, there is an abrupt change, where the disk spectrum strengthens rapidly and the Compton tail softens to $\Gamma > 2.0$. The tail can then become quite weak so that the spectrum is dominated by the disk emission with temperature $\lesssim 1$ keV, of which the Wien tail extends into the RXTE bandpass above 3 keV. This state is called the high/soft state (HSS). The source remains in the HSS as its luminosity declines, then transitions back to the LHS. This typically happens at a lower luminosity than the LHS to HSS transition, a hysteresis effect which gives a characteristic $q$ shape on a hardness-intensity diagram of the outburst (see, e.g., the compilation of Dunn et al. 2010).

In the HSS, the disk emission can be fit by the diskbb model, which approximates the standard disk (Shakura & Sunyaev 1973) by describing the local disk temperature as $T(\tau) = T_\infty \cdot (\tau/r_\infty)^{-3/2}$ (Mitsuda et al. 1984) with the maximum observed disk temperature $T_\infty$ and an apparent disk inner radius $r_\infty$. In this modeling, the disk bolometric luminosity $L_{\text{disk}}$ can be related to these two spectral parameters as $L_{\text{disk}} = 4\pi r_\infty^2 \sigma T_\infty^4$. Compelling evidence for the standard disk formalism is given by the observation that the value of $r_\infty$ remains remarkably constant in the HSS as $L_{\text{disk}}$ changes significantly. Thus, after several corrections including the stress-free inner boundary condition (e.g., Kubota et al. 1998; Gierliński et al. 1999), color temperature correction (Shimura & Takahara 1995), and relativistic corrections (Cunningham 1975; Zhang et al. 1997), $r_\infty$ is generally believed to be consistent with the innermost stable circular orbit (ISCO) around central black holes.

In contrast, in the LHS the disk emission is very weak and the luminosity is instead dominated by the hard ($\Gamma < 2$) power-law (PL) tail. The radius of the disk is hard to measure directly in this state due to model uncertainties and the weakness of the disk emission (see, e.g., Done et al. 2007). Models of this state generally assume that the inner disk progressively recedes at low luminosities and is replaced by the alternative hot inner flow solutions of the accretion flow equations (e.g., Esin et al. 1997). These models then predict that as the source transitions from the HSS toward the LHS, the disk should start to pull back from the ISCO. This cannot be observed directly in RXTE data due to the 3 keV lower limit to the bandpass. However, there is one source monitored by Swift during a transition, and here the radius of the thermal disk component clearly increases as predicted as the source declines from an HSS into the intermediate state (Gierliński et al. 2008), although the LHS radius is much more model dependent (Rykoff et al. 2007; Gierliński et al. 2008).

The intermediate states from LHS to HSS on the rise often appear quite similar to the spectra seen as the source transitions from HSS to LHS on the decline, but at higher luminosity due to the hysteresis noted above (Belloni et al. 1996; Mendez & van der Klis 1997). Some of the intermediate spectra have
steep PL tails with $\Gamma > 2.4$ leading to them; this is called the steep PL state (McClintock & Remillard 2006), although a PL is not a good approximation for the complex curvature of Comptonization seen in this state (Zdziarski et al. 2002; Gierliński & Done 2003). This state is much more common on the steep PL state (McClintock & Remillard 2006), although steep PL tails with

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Figure 1. Light curves of GX 339−4 based on the RXTE/ASM and the Swift/ 
BAT Hard X-ray Transient Monitor. Panel (a) shows the 1.5−12 keV ASM 
count rate, while panel (b) shows the ASM hardness ratio (5−12 keV/3−5 keV) 
where the points of large statistic error (∆HR > 0.7) are excluded. Panel (c) 
shows the 15−50 keV BAT count rate. A left-right arrow with vertical dashed 
lines indicates the time period during which the presented 
Suzaku data were obtained. Simultaneous observations of XMM and RXTE on 2007 February 19 
are indicated with a down arrow.

color temperature, $\kappa$, and inner boundary condition, $\xi$, gives a radius for the ISCO of $R_{\text{ISCO}} = r_{\text{in}} \cdot \kappa^2 \cdot \xi \simeq (56−73) \cdot \zeta_{50} d_{5} \text{ km,}$ taking $\kappa \simeq 1.7$ (Shimura & Takahara 1995) and $\xi = 0.37$ (Gierliński et al. 1999). The alternative approach of fitting proper radiative transfer disk models with full relativistic corrections gives similar values (Kohlemainen & Done 2010).

The disk structure in the LHS was analyzed in detail by Shidatsu et al. (2011b). They used Suzaku data of this source obtained in 2009 March and showed that the iron line features indicated an inner radius of $13.3^{+6.4}_{-6.0} R_{\text{g}}$, where $R_{\text{g}} \equiv GM/c^2$ is the gravitational radius. This corresponds to $140^{+30}_{-50}(M/7M_\odot)$ km. They also showed that weak continuum emission from the optically thick disk and surrounding coronae was consistent with the truncated disk picture with $R_{\text{in}} \sim 120 \cdot \zeta_{50} d_{5} \text{ km}$, though again we caution that this is much more model dependent than the HSS.

3. OBSERVATION AND DATA REDUCTION

As described in Section 1, the 2006/2007 outburst of GX 339−4 was its brightest outburst since the launch of RXTE in 1995 (Swank et al. 2006). Figure 1 shows the 1.5−12 keV and 15−50 keV light curve and hardness ratio of this outburst, obtained with the RXTE/ASM and the Swift/BAT Transient Monitor. The time histories of the hardness ratio and the Swift/BAT count rate suggest that the state transition occurred around MJD $\simeq 54140−54150$. The Suzaku observation was performed on 2007 February 12 05:33:31 to February 15 04:48:26, corresponding to MJD=54143.2−54146.2 as indicated with dashed lines in Figure 1. Clearly, the source hardness and the BAT count rate changed dramatically around the time of the Suzaku observation. An analysis of the QPO seen in RXTE showed a change from type C to type B on February 16 (Motta et al. 2009), so the source made a transition from VHS/HIMS to VHS/SIMS between February 15 and 16. The Suzaku spectrum and variability shows this to be a VHS/HIMS spectrum, though there is still an inflection marking the separation of disk and Compton tail (Miller et al. 2008; Yamada et al. 2009).

The XIS employed the one-fourth window option and a burst option (0.3 s for XIS0/XIS1 and 0.5 s for XIS3). The hard 

X-ray detector (HXD; Kokubun et al. 2007) was operated in the standard mode. The data processing and reduction were performed the same way as in Yamada et al. (2009), using the Suzaku pipeline processing version 2.0.6.13. To extract light curves and spectra, the data were analyzed with HEAsoft version 6.9 and the calibration data files (CALDB) released on 2007 July 10. The XIS events were extracted from a circular region with a radius of 7′ centered on the image peak. Since this extraction circle is larger than the window size of 17.8 $\times$ 4.5′, the effective extraction region is therefore the intersection of the window and this circle. As reported in detail by Yamada et al. (2009), the XIS events piled up significantly, and thus a central region of 3′ at the image center was excluded from the event extraction region to minimize these effects. Following Yamada et al. (2009), we use data from XIS0, since data from XIS1 and XIS3 are more affected by pile up than XIS0. In addition, a variable fraction of the CCD frame was often lost due to telemetry saturation, resulting in only 2.83 ks of data out of the 12.4 ks of XIS0 exposure. While Yamada et al. (2009) included data affected by the telemetry saturation to describe the iron line in detail, we excluded the telemetry saturation to avoid a small effect on the continuum shape due to the asymmetric response.

The PIN and GSO spectra, acquired for a net exposure of 87.9 ks, were corrected for small dead time, but no other correction due to the source brightness was necessary. We subtracted modeled non-X-ray backgrounds (NXBs; Fukazawa et al. 2009). The PIN and GSO background spectra were constructed based on lcfitdt and lcfit methods (2.0ver0804), respectively, filtered by the same good time intervals. As the response files, ae_HXD_PINXINOM3_20080129.rsp was used for PIN, and ae_HXD_GSOXINOM20080129.rsp and ae_HXD_GSOXINO_MCRAB_20070502.arf were used for GSO. The cosmic X-ray background was ignored since it is less than 1% of the total counts. We use GSO data only up to 200 keV, since the signal becomes smaller than 3% of the background at 200 keV. Figure 2 shows the Suzaku light curves of GX 339−4, in which background levels were subtracted and dead times were corrected for PIN and GSO data.
4. ANALYSES OF AVERAGED SPECTRUM

In this section, we present the analysis of the Suzaku spectra extracted above. To fit the observed spectra, we use the XSPEC spectral fitting package (version 12.6.0). We use energy range 0.7–9.0 keV for XIS0, 13–60 keV for the PIN spectrum, and 70–200 keV for the GSO spectrum. Large fit residuals due to calibration uncertainties are often observed near the edge structures of the XIS/XRT instrumental responses, so we exclude XIS data from 1.4–2.3 keV. We fit the three spectra simultaneously, with constant factors scaling between the three fixed at 1, 1.07, and 1.07 for XIS, PIN, and GSO, respectively.6 We extend the energy range of the spectral fitting to 0.1–1000 keV, as we use some convolution models. Such models have edge effects at the end of the energy range used for the calculation, so it is important that the edge energy is beyond the energy range used for the data.

4.1. Empirical Modeling by diskbb and power-law with Reflection (Model 1)

In order to characterize the spectral shape, we first model the 0.7–200 keV Suzaku data in the same way as Yamada et al. (2009), i.e., the diskbb model plus PL model. We hereafter call this “model 1.” The two continuum components are both absorbed by a common hydrogen column modeled with the xspec WABS model (Morrison & McCammon 1983). While Yamada et al. (2009) used the laor model to describe the iron line in detail, we use a single Gaussian with $\sigma$ at 0.2 keV since we focus on the continuum shape; our much shorter exposure (due to more stringent constraints on telemetry issues) means that the spectra have much lower statistics.

To account for ionized reflection of the PL component, we utilized the model ireflect (a convolution version of the pexriv model; Magdziarz & Zdziarski 1995). This model balances photoionization with radiative recombination from the very simplistic ionization balance code of Done et al. (1992). This requires a user-defined (rather than self-consistently computed) temperature, which we set to $10^6$ K as the disk is clearly hot. However, the code does not calculate collisional processes, so the ion population is set only by photoionization. This is clearly a poor assumption for such a hot disk. Thus, the fairly high ionization parameter required by Yamada et al. (2009) may be an overestimate of the required illuminating flux. Yet another limitation is that the model does not include Compton scattering within the disk, which has quite a large effect on the characteristic iron line and edge profile in the reflected emission. Photoionization heats the disk photosphere to some fraction of the Compton temperature, so this can be of the order of $\sim$1 keV for high ionization parameters. All the line/edge features are produced at an optical depth of around unity, so this means that a third of the photons are Compton scattered by these hot electrons, smearing the sharp line/edge seen in ireflect/pexriv (Ross et al. 1999; Ross & Fabian 2005). This may mean that the relativistic smearing is overestimated, but we caution that generally spectral parameters are all interrelated, so it may instead distort the observed solid angle, ionization state, or iron abundance. Despite these drawbacks, there are few better alternatives at present. The models at high densities of Ross & Fabian (2007) are not yet public.

We fix the ionization parameter 300 erg cm s$^{-1}$ and fix all abundances other than iron at solar. Hence, the only free parameters are the amount of solid angle and the iron abundance. We smear this reflected spectrum by general relativistic effects using rdbblur (Fabian et al. 1989). We fix all the parameters of this at characteristic values seen by Yamada et al. (2009), i.e., inner and outer radius $R_{\text{in}}^{\text{blur}} = 10R_g$, $R_{\text{out}}^{\text{blur}} = 10^5 R_g$, inclination angle $i = 50^\circ$, and power law index of emissivity $\beta = -3$, as our limited data quality do not allow us to constrain them independently.

Table 1 gives details about how the model was described in xspec, while Table 2 gives the best-fit parameters. This shows that model 1 fits the data well with $\chi^2/\text{dof} = 190.2/186$. Figure 3 shows the data and the best-fit model and residuals, while Figures 4 and 5(a) show the $\nu F_\nu$ spectrum and unabsorbed

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$^6$ http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/watchout.html
model spectrum, respectively. The absorbed 0.7–200 keV flux is estimated as 2.8 × 10⁻³⁸ erg s⁻¹ cm⁻², which gives an absorbed luminosity of 2.1 × 10⁶⁸ erg s⁻¹ assuming isotropic emission. The PL photon index Γₚl = 2.68±0.02; this and the high luminosity mean that the source is in the VHS, as noted by Yamada et al. (2009). The best-fit parameters are consistent with those obtained by Yamada et al. (2009) within 90% confidence, and the best-fit diskbb model shows disk inner temperature of $kT_{in} = 0.65 ± 0.02$ keV and an apparent inner radius of $r_{in} \sim (56\pm9)$ km, consistent with that observed in the usual HSS (52–68) · $\xi_0d_{k}$ km (see Section 2).

However, an inspection of Figure 5(a) shows that this is not a good physical description of a model where the disk provides the seed photons for Compton upscattering into the PL tail, as the PL extends below the disk at low energies. This motivates further studies of the disk structure with more physical models.

### 4.2. Disk Geometry Based on Independent Corona (Model 2 and Model 3)

Compton scattering conserves photon number, so it removes seed photons from the observed spectrum by boosting them in energy to form the Compton tail. We replaced the PL model with a convolution model simpl (Steiner et al. 2009), which self-consistently removes as many seed photons as it puts into a Compton tail. This is identified as “model 2” in Table 1. As
described in Table 1, only the upscattered photons are reflected by the optically thick disk and are thus modified by the models of rdblur and ireflect. The fit results are presented in Table 2 and Figure 3(c). As shown in the unabsorbed model spectrum (Figure 5(b)), this gives a more physical description of the distribution of the low-energy photons. The lack of emission at the lowest energies from Comptonization compared to a PL means that the disk temperature becomes lower to compensate for this, with $kT_m = 0.55^{+0.02}_{-0.01}$ keV, and the radius becomes higher $r_m = (122^{+7}_{-8}) \cdot \zeta_5 d_8$ km. This implies that the disk inner radius is twice as large as the ISCO in comparison to that found in the usual HSS.

However, the Comptonization seen in the VHS is complex, containing a mix of both thermal and non-thermal electrons (e.g., Gierliński et al. 1999; Kubota et al. 2001; Gierliński & Done 2003), whereas the simpl model used above only makes a non-thermal PL tail. Hence, we added a thermal Comptonization model, nthcomp (Zdziarski et al. 1996; Zycki et al. 1999), to the model (model 3 in Table 1). This has four parameters, the seed disk photon temperature, which we tie to the seed photon temperature of diskbb, the electron temperature $kT_e$, photon index $\Gamma_{th}$ (equivalent to optical depth), and normalization. The relation between the optical depth, electron temperature, and spectral index is given by Equation (A1) of Zdziarski et al. (1996) assuming a spherical source with a uniform distribution of seed photons throughout the source. In contrast, we assume slab geometry with seed photons at the bottom of the slab. Comparing these two geometries with compps (geom = −4 and 1, respectively, Poutanen & Svensson 1996) shows that the spectral indices are equivalent for an optical depth in the slab geometry that is approximately half that of the sphere. Hence we use

$$\tau = \frac{1}{2} \cdot \left( \frac{9}{4} + \Theta_e \cdot \left( \frac{3}{(\Gamma_{th} + \frac{1}{2})^2 - \frac{9}{4}} \right) - \frac{3}{2} \right),$$

where $\Theta_e = kT_e/m_e c^2$.

We cannot uniquely constrain both $\Gamma_{th}$ from the thermal Comptonization and $\Gamma_{pl}$ from simpl so we fix the latter at 2.1, the value of the non-thermal tail seen in the typical HSS (Gierliński et al. 1999). The non-thermal tail may be somewhat steeper in the VHS and again has a complex shape (Gierliński & Done 2003). However, our data do not extend above 200 keV, so we are not very sensitive to this. Hence, model 3 has only two additional free parameters. Similar to
models 1 and model 2, only the Comptonized emission is reflected by the underlying optically thick disk, and thus the model description is somewhat complicated as described in Table 1. This gives \( \chi^2 / \text{dof} = 192.0/184 \), which is still not as good as model 1 but is better than model 2. The fits are shown in Table 2 and Figures 3(d) and 5(c). These show that the thermal Comptonization dominates the spectrum below \( \sim 50 \) keV.

Unlike \textsc{simp}, the thermal Comptonization does not decrease the seed photon spectrum. Hence, we have to manually adjust the disk normalization for the photons which are scattered out into the thermal Compton tail. Hence, we also tabulate the unabsorbed photon flux \( F_{\text{photon}}^\text{disk} \) contained in the thermal Compton tail integrated from 0.01 to 100 keV. We assume that these photons were removed equally from all energies of the disk spectrum (equivalent to a uniform corona over the entire disk). The observed photon flux from the disk \( F_{\text{photon}}^\text{disk} \) is also tabulated, and we simply increase the measured disk normalization by this amount. Since the normalization is proportional to the square root of the radius, this gives an inferred radius \( r_{\text{in}}^* = r_{\text{in}} \sqrt{(F_{\text{photon}}^\text{disk})/(F_{\text{photon}}^\text{disk})} \), where \( r_{\text{in}} \) is calculated from the unabsorbed disk luminosity alone. This is equivalent to Equation (A.1) in Kubota & Makishima (2004), and it gives \( r_{\text{in}}^* = (117 \pm 5) \cdot \xi_5 d_5 \) km, which is as large as that estimated with model 2.

4.3. Inner Disk–Corona: Coupled Energetics (Model 4)

The previous two models assumed that the Comptonizing electrons fully covered the disk and that the underlying disk structure is unaffected by the presence of the high-energy electrons. However, both these assumptions are probably not appropriate. The corona probably only covers the inner disk at \( r_{\text{in}} < r < r_{\text{tran}} \) as schematically shown in Figure 6. The power in the corona also must ultimately derive from the accretion flow, so there should be less power dissipated in the disk.

In the view of these concepts, we fit the data by replacing the “\textsc{diskbb+nthcomp}” components in model 3 with the coupled disk–corona model, \textsc{dkbbfth}, given by Done & Kubota (2006) (model 4 in Table 1). This model assumes that the energy released by gravity is dissipated locally, either thermalizing in the disk for \( r > r_{\text{tran}} \) or split between the disk and corona for \( r_{\text{in}} < r < r_{\text{tran}} \), as shown schematically in Figure 6. Thus, the disk underlying the corona is cooler and less luminous than it would have been if the corona did not exist, and it is this weak and cool disk emission which provides the seed photons for the Compton upscattering (see Svensson & Zdziarski 1994; Done & Kubota 2006).

The model parameters are similar to those in a \textsc{diskbb+nthcomp} continuum (model 3), except that rather than having two separate normalizations, the parameters that control the relative normalization of the disk and corona are a combination of \( r_{\text{tran}} \), which determines the outer, unComptonized disk luminosity, and the shape of the thermal Comptonization, i.e., \( \Gamma^\text{th} \) (equivalent to \( \gamma \)) and \( kT^\text{th} \). The luminosity of the Compton component, \( L_{\text{th}} \), is approximately determined by the Compton \( \gamma \) parameter where \( \gamma \approx 4\Omega(r + r^2) \) as \( L_{\text{th}} = y L_{\text{disk,in}} \) and \( L_{\text{disk,in}} \) is the inner disk luminosity for \( r_{\text{in}} < r < r_{\text{tran}} \). Thus, the ratio of power dissipated in the corona to that of the disk in the region \( r_{\text{in}} < r < r_{\text{tran}} \) is \( L_{\text{disk}} / L_{\text{disk,in}} \), \( \approx \gamma \) (see Done & Kubota 2006 for examples of how the model spectra change as a function of these parameters). The inner radius is calculated via Equation (A.1) in Kubota & Makishima (2004) by replacing \( \gamma L_{\text{disk}} + F_{\text{th}}^\text{disk} \cdot 2 \cos \theta \) with photon flux of the \textsc{dkbbfth} component, \( F_{\text{photon}}^\text{dkbbfth} \), assuming the slab geometry. The radius is also determined from the intrinsic (rather than observed) innermost disk temperature, \( T_{\text{in}}^\text{int} \). This is how the entire disk would be seen if there were no energy dissipated in the corona.

This model only takes into account the thermal Comptonization, so we again include the \textsc{simp} with fixed \( r_{\text{in}} = 2.1 \) to describe the non-thermal tail. In this analysis, we set the unscattered component of the \textsc{dkbbfth} to be seed photons for \textsc{simp}. Again, both the thermal (\textsc{dkbbfth}) and non-thermal (\textsc{simp}) Compton components are modified by the ionized reflection and blurred by the relativistic effects.

The model has the same number of free parameters as model 3, but it gives an improved fit with \( \chi^2 / \text{dof} = 178.7/184 \). This is the best \( \chi^2 \) value among the four models despite the fact that the model is more constrained. The fit results are summarized in Table 2 and Figures 3(e) and 5(d). With the best-fit parameters given by assuming an isotropic emission, the absorbed and unabsorbed luminosity was estimated in the range of \( 0.7–200 \) keV as \( 2 \times 10^{38} \) erg s\(^{-1}\) and \( 2.9 \times 10^{38} \) erg s\(^{-1}\), respectively. We also calculated the bolometric luminosity (3.8 \( \times 10^{38} \) erg s\(^{-1}\) and the optical depth of \( \tau = 0.58^{+0.08}_{-0.07} \) using Equation (1). The corona was found to be localized within \( r_{\text{tran}} \) of 2.7\( r_{\text{in}}^* \) within which 27% of the accretion power is dissipated in the thermal corona.

Considering the power dissipated in the corona, the intrinsic disk temperature should be \( kT_{\text{in}}^\text{int} = 0.67^{+0.03}_{-0.08} \) keV. With this intrinsic disk temperature and the 0.1–100 keV \textsc{dkbbfth} photon flux of \( F_{\text{photon}}^\text{dkbbfth} = 43.5 \) photons s\(^{-1}\) cm\(^{-2}\), the underlying disk inner radius was estimated as \( r_{\text{in}}^* = (93^{+19}_{-17}) \cdot \xi_5 d_5 \) km. In Figure 5(d), the intrinsic disk emission is plotted with a dashed-dotted line. Though the estimated apparent inner radius is slightly smaller than that obtained with independent corona modeling (models 2 and 3), it is \( \sim 1.3–2.2 \) times larger than that observed in the HSS (see Section 2).

We checked that the results were not affected by the assumption that relativistic blurring has a radial dependence parameterized by \( \beta = -3 \). We replaced this by \( \beta = 10 \), which is...
more appropriate for a stress-free inner boundary condition, assuming that the line emissivity is proportional to the local energy release rate in the disk. The difference from the $\beta = -3$ case was negligible. Even entirely removing relativistic effects does not change the continuum parameters significantly due to the limited statistics around the iron line/edge in our data. In all cases the best-fit disk parameters were still consistent with those shown in Table 2.

5. IS THE DISK TRUNCATED IN THESE DATA?

All the models above which self-consistently correct the disk normalization for Compton scattering (models 2, 3, and 4) find a disk inner radius which is larger than that seen in the HSS in this source. This can be seen directly by comparison with an HSS spectrum at a very similar luminosity. Figure 7(a) shows the Suzaku data used here together with the HSS spectrum of almost the same luminosity taken by XMM and RXTE on February 19 (Kolehmainen et al. 2011; see Figure 1). Figure 7(b) shows the comparison of the unabsorbed model spectra.

The HSS spectrum is roughly characterized by a dominant diskbb of $kT_{\text{in}} \simeq 0.82$ keV with a weak PL tail, and an absorbed 0.7–200 keV flux is estimated as $2.4 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$, which is only 15% lower than the Suzaku flux of $2.8 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ in the same energy band. Thus, if the disk has a constant radius between the HSS and VHS/HIMS, then the disk temperature should be slightly higher in the higher luminosity VHS/HIMS. Yet is it clear from this figure that the VHS disk has a lower temperature, as the data peak at lower energy in Figure 7(a). Compton scattering retains the imprint of the seed photon energy, so this lower temperature cannot be a consequence of simply Comptonizing the higher temperature inner disk (see Done & Kubota 2006). The blue dash-dotted line in Figure 7(b) shows the estimated intrinsic disk emission from the VHS/HIMS data as reconstructed from the kbbp7th model, i.e., how the disk emission would have looked in the Suzaku data if the thermal corona were not present and the matter of thermal corona were all accreted in the disk. If the inner radius is kept constant between the HSS and VHS/HIMS, the intrinsic disk emission should peak at higher energy than in the HSS. However, the peak energy of the intrinsic disk emission is still much lower than that in the HSS. Estimated intrinsic VHS disk temperature $kT_{\text{in}} = 0.67^{+0.04}_{-0.08}$ keV is much lower than the observed HSS disk temperature of $kT_{\text{in}} \simeq 0.82$ keV. Therefore, the apparent inner radius of the VHS/HIMS is clearly larger than that in the HSS.

To convert from apparent to true inner disk radius requires corrections for the color temperature, $\kappa$, and inner boundary condition, $\xi$, with $R_{\text{in}} = r_{\text{in}} \cdot k^2 \cdot \xi$ as described in Section 2. If we use the same $\kappa$ and $\xi$, we obtain $R_{\text{in}} = (99^{+20}_{-16}) \cdot \xi_{50} d_8$ km. Under the same value of $\xi$, the only way to get the same inner radius of the disk in the VHS/HIMS as that in the HSS is if $\kappa$ is as low as $\sim 1.3$–1.4. This seems very unlikely given the strong illumination. On the contrary, it is certainly plausible that the disk color temperature correction has increased substantially, as the inner disk should be strongly illuminated by the Comptonized emission in the VHS/HIMS, whereas it is not in the HSS. This only reinforces the change in true inner radius as a larger color temperature correction means that $R_{\text{in}}$ is even larger than that derived assuming $\kappa = 1.7$. Similarly, if the disk is truncated, then the use of the same boundary condition is not appropriate as it now does not extend down to the ISCO, where there is the stress-free inner boundary, but is truncated where there can still be stress on the inner boundary, making $\xi$ larger. This again leads to an increase in $R_{\text{in}}$ (see also the discussion in Gierviński et al. 2008).

Thus, both of the expected changes in color temperature and inner boundary condition reinforce the conclusion that the disk inner radius is larger in the VHS/HIMS than in the HSS. Using $\kappa = 1.9$ (Shimura & Takahara 1995) and $\xi = 1$ as a reference, $R_{\text{in}}$ can be as large as $\sim 340 \cdot \xi_{50} d_8$ km.

6. VARIABILITY OF THE DISK AND CORONA

6.1. QPO Frequency

Figure 8(a) shows the power spectral density from the entire PIN light curve calculated using xronos (version5.22). In this figure, a double QPO feature is seen at frequencies of $\sim 4$ Hz and $\sim 5$–6 Hz. During the observation, PIN and GSO count rates slightly decreased by $\sim 25\%$ and $\sim 18\%$, respectively, while that of XIS-0 slightly increased $\sim 9\%$ (Figure 2). Thus, the double QPO feature is probably due to a change of a single QPO frequency.
We reanalyzed the same data by dividing them into the first half and the latter half as indicated in Figure 2. The calculated power spectral densities are also shown in Figures 8(b) and (c), showing a clear change in QPO frequency from $4.26 \pm 0.06$ Hz in the first half to $5.46 \pm 0.06$ Hz in the second half. Since these QPO frequencies are probably set by the size of the emission region, we looked for changes in the size of the disk and corona in their corresponding spectra. Specifically, a higher frequency QPO should indicate a smaller size region, and our modeling with DKBFBTH means that we can track both the size of the disk and the size of the corona via the parameters $r_{in}$ and $r_{tran}$. We then compared the observed changes with the predictions of two specific QPO models.

### 6.2. Time Evolution of Spectral Parameters

To investigate evolution of the disk and corona in detail, we accumulated spectra from the two halves of the observation. For PIN and GSO data, net exposures of 43.9 ks and 44.0 ks were acquired for the first half and the latter half, respectively. The NXB spectra were calculated for each period and subtracted from the data. For XIS0 data, 1.6 ks and 1.3 ks exposures were acquired for the first half and the latter half, respectively. The two data sets have very similar observed luminosities. The absorbed flux was almost the same at $2.7 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ and $2.8 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ for the first half and the latter half, respectively, while their spectral shape was clearly different. The top panel of Figure 9 shows $\nu F_\nu$ spectra of the first half (green) and the latter half (orange), and the bottom panel shows ratios of each spectrum to the best-fit model 4 for the summed spectrum. There is a clear anti-correlation between the soft band data and the hard band data. The XIS0 data in 1–4 keV increased, while the PIN data decreased, so the spectrum pivots around 10 keV, becoming significantly softer during the Suzaku observation.

A closer inspection of Figure 9 reveals that the data below 1 keV do not take part in this spectral pivoting, but instead remain relatively stable despite the 10%–20% flux change in the range of 2–4 keV. These photons below ~1 keV are from the outer part of the disk, where the local temperature is lower than ~0.3 keV. Since this emission does not change, it seems most likely that the mass accretion rate through the disk is not changing (as is also implied by the constant luminosity), and it is only the geometry of the inner disk/corona that gives the spectral change above 1 keV.

In order to discuss the change in the spectral parameters, we fit the two data sets with the independent corona (model 3) and the coupled corona (model 4). We fixed the values of $N_{\text{H}}$, iron abundance, and the Gaussian central energy at the best-fit values obtained by the summed spectral fit (Table 2). Furthermore, in the case of model 4, to avoid a strong coupling between $\tau$ and $kT_e$, we fixed $kT_e$ to the value seen in the average spectrum.

The results are summarized in Table 3: again, the energetically coupled corona model DKBFBTH gives the best fit. Based on the best-fit model 4, the photon index of thermal corona $\Gamma_{th}$ increases from 2.59 ± 0.03 to 2.74 ± 0.04. Since we keep $kT_e$ constant between the two data sets, this means that the optical depth of the thermal corona $\tau$ slightly decreased from $0.61 \pm 0.02$ to $0.55^{+0.02}_{-0.01}$. Hence, the second half of the data have a lower $\gamma$ parameter and a softer Compton tail, as seen in Figure 9. This means that $f_{th}$ also decreases from 0.30 to 0.25. The unComptonized disk emission is slightly more prominent in the second spectrum, so the transition radius decreases slightly from $r_{tran} = (2.6^{+0.6}_{-0.5}) r_{in}$ to $(2.3^{+0.4}_{-0.2}) r_{in}$.

The intrinsic disk temperature $kT_{in}^{int}$ marginally increases from 0.66 ± 0.03 keV to 0.69$^{+0.02}_{-0.01}$ keV, giving an apparent inner radius of the underlying disk, $r_{in}^{int}$ which decreases by ~5% from $(95^{+7}_{-5})$ km to $(90^{+6}_{-4})$ km. Thus, the outer radius of the corona $r_{tran}$ decreases by ~16% from 250 · $\xi_{50}$ km to 210 · $\xi_{50}$ km. Model 3 gave a similar result in that the disk inner radius decreased ~5% from the first half to the second half data.

### 6.3. Discussion on the Relation of QPO and the Thermal Corona

Lense–Thirring precession has been proposed as the origin of the low-frequency QPOs (e.g., Stella & Vietri 1998). This can
explain both the frequency and the spectrum of the QPO if the precession is of a hot inner Compton flow rather than the thin disk (Ingram et al. 2009). In this model, the QPO frequency $f_{\text{QPO}}$ is $f_{\text{QPO}} \propto r^{-2.1}$. Thus, a 28% ± 3% increase in QPO frequency means that the size of the precessing region should decrease by ~11%±1%. Since the precession is a vertical mode, the only part of the corona that can precess in this way is the corona interior to $r_{\text{in}}^*$ (see the schematic diagram in Figure 6). The fits imply that $r_{\text{in}}^*$ decreases by ~5%±8%, consistent with the Lense–Thirring QPO model.

Another model for the low-frequency QPO is one in which it is a mode of the hot inner flow. Global three-dimensional magnetohydrodynamic (MHD) simulations suggest that the magnetorotational instability may lead to the quasi-periodic deformation of a hot inner torus from a circle to a crescent (Machida & Matsumoto 2008). The frequency in their simulation can be roughly related to the size of the inner torus $r_{\text{in}}(\zeta_{\text{2D}0})$ km). The low-frequency QPO increases from 4–16 Hz to 2.6–10 Hz.

7. SUMMARY AND CONCLUSIONS

We have analyzed the Suzaku spectrum of GX 339–4 in the strongly Comptonized VHS/HIMS. We used a series of models to fit the data, starting with the commonly used "diskbb plus PL" model (model 1). We then used progressively better models of the Comptonization, first assuming that it is non-thermal (model 2) and then allowing it to be both thermal and non-thermal (model 3) as required from previous studies (e.g., Zdziarski et al. 2001; Gierliński & Done 2003). The strong Comptonization means that many seed photons from the disk are removed by Compton scattering so the disk luminosity is larger than the directly observed luminosity. This effect increases the apparent radius of the disk, though using proper Comptonization models rather than a PL already increases the disk luminosity and gives an apparent radius that is larger than that seen in the HSS. Our final model couples the disk and corona together (model 4).

All of the models except for model 4 assume that the disk and corona are independent components that both ultimately derive from the gravitational energy. Hence, our final model is a more physical one in which an inner corona reduces the power available for the inner disk. This more physical model gives the best fit to the data and again requires that the apparent radius of the disk is larger than that seen in the HSS. This increase in apparent size of the disk can be seen directly by comparison with an XMM-Newton/RXTE HSS spectrum at almost the same luminosity taken three days after the Suzaku data. This clearly shows that the disk temperature is lower in the VHS/HIMS than in the HSS. The only way that this can be consistent with the same true inner disk radius is if the color temperature correction and/or stress at the inner boundary decreases in the VHS/HIMS. However, it is much more likely that these actually increase, as there is strong irradiation in the VHS/HIMS that should increase the color temperature correction, and it is not possible to decrease the stress on the inner boundary from the zero stress condition used for the HSS. Thus, the data show that the VHS/HIMS is associated with a truncated cool disk geometry, where the disk inner radius is 1.3–2.2 times larger than that of the constant radius seen in the HSS, which is identified with the ISCO.

Within the Suzaku observation there is a small change in flux and spectral shape and a corresponding change in the fast variability properties as determined from the power spectrum. The low-frequency QPO increases from 4.26 ± 0.06 Hz to

| Component | Parameter | Model 3 | Model 4 | Model 3 | Model 4 |
|-----------|-----------|---------|---------|---------|---------|
| Diskbb    | $kT_{\text{in}}$ (keV) | 0.54 ± 0.01 | 0.58+0.02|0.01 | ... | ... |
|           | $r_{\text{in}}$ (\zeta_{\text{2D}0}) km | 99±3 | 91 ± 3 | ... | ... |
| NTHcomp of Diskbb | $kT_{\text{in}}$ (keV) | ... | ... | 0.66 ± 0.03 | 0.69+0.05|0.03 | ... | ... |
|           | $\Gamma_{\text{in}}$ | 2.63+0.03|0.04 | 2.80+0.04|0.05 | 2.59 ± 0.03 | 2.74 ± 0.04 |
| Norm      | 38±11 | >41 | (41)* | (41)* |
|           | $r_{\text{in}}(\zeta_{\text{2D}0})$ km | ... | ... | 2.6±0.4 | 2.3±0.4 |
| Derived $\tau$ | 0.6 ± 0.3 | <0.55 | 0.61 ± 0.02 | 0.55+0.02|0.01 |
| Derived $f_{\text{in}}$ | ... | ... | 0.30 | 0.25 |
| SIMPL     | $\Gamma_{\text{PL}}$ | (2.1) | (2.1) | (2.1) | (2.1) |
|           | $f_{\text{PL}}$ | 0.058+0.005|0.003 | 0.035+0.003|0.004 | 0.035 ± 0.002 | 0.028 ± 0.002 |
| IREFLECT  | $\Omega/2\pi$ | 0.76+0.09|0.01 | 0.88+0.11|0.04 | 0.66+0.06|0.08 | 0.82 ± 0.10 |
| Gaussian  | $\chi^2$/dof | 185.1/184 | 190.9/184 | 180.5/185 | 184.6/185 |
| Inner radius | $F_{\text{disk}}$ (photons s$^{-1}$ cm$^{-2}$) | 38.7 | 41.1 | 43.0 | 44.3 |
|           | $r_{\text{in}}$ (\zeta_{\text{2D}0}) km | 122±5 | 116±5 | 95±6 | 90±6 |

Notes. Same as Table 2 but for the separated spectra fit with models 3 and 4.

* Fixed at the best-fit values for the summed spectrum in Table 2.
5.46 ± 0.06 Hz as the spectrum softens, with a derived decrease in apparent disk inner radius of \( r_\text{in} = (95^{+7}_{-5}) \cdot \xi_{SO} d_h \) km to \((90^{+6}_{-4}) \cdot \xi_{SO} d_h \) km. While this is not significant, this decrease in radius is consistent with the increase in QPO frequency if the QPO is formed either from a Lense–Thirring precession of the hot flow interior to \( r_\text{in} \) (Ingram et al. 2009) or from an MHD mode of this flow (Machida & Matsumoto 2008).

A slightly truncated disk in the VHS/HIMS clearly makes a smooth connection to a larger radius disk truncation as required for LHS models, which use the alternative hot flow solutions (Esin et al. 1997), making a coherent picture of the outbursts of BHB in a model in which the spectrum changes from LHS–VHS/HIMS–HSS driven by a decreasing inner disk radius until it reaches the ISCO.

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