SWIFT AND RXTE OBSERVATIONS OF THE BLACK HOLE TRANSIENT GX 339-4 IN THE HARD STATE BETWEEN OUTBURSTS

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Received 2012 December 18; accepted 2013 July 12; published 2013 August 26

ABSTRACT

We use simultaneous Swift and RXTE observations of the black hole binary GX 339-4 to measure the inner radius of its accretion disk in the hard state down to 0.4% $L_{\text{Edd}}$ via modeling of the thermal disk emission and the relativistically broadened iron line. For the luminosity range covered in this work, our results rule out a significantly truncated disk at 100–1000 $R_g$ as predicted by the advection-dominated accretion flow paradigm. The measurements depend strongly on the assumed emission geometry, with most results providing no clear picture of radius evolution. If the inclination is constrained to roughly 20°, however, the measurements based on the thermal disk emission suggest a mildly receding disk at a luminosity of 0.4% $L_{\text{Edd}}$. The iron abundance varies between ~1 and 2 solar abundances, with the $i = 20°$ results indicating a negative correlation with luminosity, though this is likely due to a change in disk illumination geometry.

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

Online-only material: color figures

1. INTRODUCTION

Stellar mass black holes are typically observed in binary orbits with a companion star. Accretion of material from the companion star onto the black hole forms an accretion disk, which converts gravitational energy into radiation primarily in the X-ray band. Accretion in black hole binaries (BHBs) can be a sporadic process, resulting in X-ray outbursts separated by periods of low luminosity. As a BHB evolves over time, it can be observed to transition between three canonical emission states: thermal, hard, and steep power law (Remillard & McClintock 2006). The thermal state is generally characterized by high luminosity, a thermally dominated spectrum, and low levels of X-ray variability. In the hard state, sources have spectra dominated by a power-law component, relatively high X-ray variability, and are frequently accompanied by compact radio jets (Fender 2006). While the hard state is typically seen at low levels of luminosity at the beginning or end of an outburst, a source can remain in the hard state even at high luminosities (Homan et al. 2001; Fender et al. 2004; Tomsick et al. 2005; Dunn et al. 2010). The steep power law is not well understood, occurring at high luminosities with strong variability in the form of quasi-periodic oscillations (van der Klis 2006) and a steep power-law index. Note that BHBs are also frequently classified as spectral hardness and intensity (e.g., Belloni 2010).

The common framework for understanding BHB state transitions is described in Esin et al. (1997). Within this model, BHBs are usually found in the hard state at low accretion rates ($\dot{m} \lesssim 0.01 M_{\text{Edd}}$). The inner part of the accretion disk is optically thin and is characterized by low density, possibly caused by radiative evaporation (Meyer et al. 2000). Most of the viscously released energy is contained in the ions, which are unable to radiate efficiently in an advection-dominated accretion flow (ADAF). This results in energy being advected toward the black hole rather than being radiated away. Additionally, the flow becomes spherical due to the high pressures expected in the ion gas. At these low accretion rates, the thermally dominated accretion disk is predicted to be truncated at an inner radius on the order of 100–1000 $R_g$ ($R_g = GM/c^2$). At higher mass accretion rates (thermal state), the accretion disk reaches all the way down to the innermost stable circular orbit (ISCO). The precise luminosity and/or mass accretion rate at which the truncation occurs, if at all, is still a matter of debate (Miller et al. 2006a; Rykoff et al. 2007; Tomsick et al. 2008; Reis et al. 2010).

One way to test for the presence of an ADAF involves measuring the inner radius of the thermally dominated accretion disk of BHBs at low luminosities. The thermal emission of the disk is dependent on both its inner temperature and inner radius, and modeling the shape of the thermal component in low-luminosity BHB spectra can provide measurements of both. This is complicated, however, due to the power-law domination of BHB spectra in the hard state; the low normalization and temperature of the thermal component are difficult to constrain. There are also uncertainties in corrections required by spectral hardening via scattering in the corona and general relativistic boundary conditions at the inner radius (Kubota et al. 1998; Shimura & Takahara 1995). Another method of radius measurement uses the shape of the relativistically broadened iron line (Fabian et al. 1989). The effect of relativistic broadening as a function of disk geometry has been calculated by Laor (1991), but models based on these calculations fail to include thermal broadening inherent to the line. A model has been incorporated into XSPEC that includes thermal broadening (reflionx; Ross & Fabian 2005) and also calculates the emission lines and continuum due to reflection of emission off of the disk in a physically self-consistent manner.

GX 339-4 is a galactic BHB with a persistent iron line in its various emission states. The distance has been estimated to be 6 kpc $< D < 15$ kpc by Hynes et al. (2004) via analysis of
the Na and Ca lines in the optical spectrum of the companion star. Hynes et al. (2003) calculated the mass function to be 5.8 $M_\odot$ using radial velocity data of the companion star. There is debate in the literature regarding the inclination, with some results at $\sim$20°–30° (Miller et al. 2006b; Done & Diaz Trigo 2010), and a more recent study favoring $\sim$50° (Shidatsu et al. 2011). There is also debate on the inner accretion disk radius of GX 339-4 at low luminosities. Tomsick et al. (2009) have measured the radius at the lowest luminosity (0.14% $L_{\text{Edd}}$) and find a significantly truncated disk at $>65R_g$. At slightly higher luminosities ($\sim$2%–4% $L_{\text{Edd}}$), however, several results indicate a disk radius consistent with the ISCO (Miller et al. 2006b; Reis et al. 2008), while Shidatsu et al. (2011) find a marginally truncated disk at $13.3^{+6.4}_{-1.0}R_g$. This paper examines the inner disk radius of GX 339-4 using both thermal modeling and relativistic line broadening at a variety of luminosities in the hard state.

2. OBSERVATIONS AND DATA REDUCTION

We analyzed Swift X-ray Telescope (XRT; Burrows et al. 2005) and RXTE Proportional Counter Array (PCA; Jahoda et al. 2006) observations of GX 339-4 between its 2007 and 2010 outbursts. The observations span 2007 May 24 to 2010 March 6 (MJD 54244–55261), with total exposures of 52,628 s and 114,160 s for the XRT and PCA, respectively. The data was reduced using HEASOFT v6.11. PCA spectra were extracted using marfast, with marfast 3.2.6 used to produce the response matrices and the SkyVLE model to produce the background spectra. XRT spectra were extracted using xselect, with xrtmkarf_0.5.9 as the response and xrtmkarf_0.5.9 to produce the ancillary response file. Due to the proximity of GX 339-4 to the Galactic plane, observations from 2001 March, 2002 February, and 2003 September were used to create a quiescent spectrum that was subtracted from all PCA spectra. To improve statistics, data were combined into seven PCA/XRT spectra as indicated by Table 1. The PCA and XRT light curves are shown in Figure 1 with boxes indicating spectral groupings. Spectral fitting was performed in XSPEC v12.7.1. XRT spectra were restricted to 0.5–10 keV and PCA spectra to 3–25 keV. Systematic errors of 0.5% were added to the PCA spectra.

3. RESULTS

3.1. Spectral Model and Fitting Procedure

To investigate the possible presence of an iron line, we examined the residuals in the 5–8 keV range. Specifically, all seven spectra were fit with an absorbed multicolor blackbody disk model plus a power-law component, the standard model for BHBS (Remillard & McClintock 2006). The data/model ratios in Figure 2 show a clear, broad peak near 6–7 keV in the PCA data. The peak is also evident in the XRT residuals, except in spectra 3 and 4. The PCA residuals above 10 keV show a positive deviation from the power law, a feature typical of disk reflection. Confident in the presence of a broad iron line in all seven spectra, we switched to a model including iron line emission with relativistic blurring and disk reflection.

PCA and XRT spectra were fit simultaneously using an absorbed (phabs) multicolor blackbody disk model (diskbb; Mitsuda et al. 1984) plus a standard power-law component. The Wilms et al. (2000) interstellar medium abundances and Balucinska-Church & McCammon (1992) photoelectric cross sections were used in the phabs component. Spectral features due to reflection of the power-law component off of the disk were modeled using reflionx (Ross & Fabian 2005). reflionx assumes a folding energy of 300 keV in the power law, which was included with the multiplicative component highcut. The power law and reflection model components were convolved with kdblur (a relativistic broadening model

Table 1

| Observation # | MJD Start | MJD End | XRT Exposure | XRT Rate (counts s⁻¹) | PCA Exposure | PCA Rate (counts s⁻¹) |
|--------------|-----------|---------|--------------|-----------------------|--------------|----------------------|
| 1            | 54244.7   | 54260.0 | 7119 s (2 obs) | 11.54 | 7984 s (3 obs) | 60.79 |
| 2            | 54261.7   | 54282.0 | 14830 s (7 obs) | 3.06 | 49952 s (24 obs) | 20.89 |
| 3            | 54285.2   | 54292.6 | 3854 s (3 obs) | 4.61 | 9344 s (8 obs) | 37.00 |
| 4            | 54299.7   | 54313.9 | 4985 s (5 obs) | 7.36 | 12800 s (8 obs) | 57.25 |
| 5            | 54897.6   | 54932.2 | 14184 s (10 obs) | 10.39 | 14784 s (6 obs) | 84.90 |
| 6            | 55217.7   | 55218.0 | 4756 s (1 obs) | 14.97 | 2800 s (1 obs) | 102.6 |
| 7            | 55260.0   | 55261.1 | 2900 s (4 obs) | 39.72 | 16496 s (5 obs) | 252.6 |

Figure 1. PCA X-ray count rate taken from the RXTE Bulge Scans Web site is shown on both a linear (top) and logarithmic (middle) scale from late-2006 to mid-2010. The energy range covers 2–10 keV from five PCUs. The XRT X-ray count rate is shown over the same time period on the bottom, with boxes indicating the grouping of the seven spectra in this paper. Spectra 1 and 2 contain observations from Tomsick et al. (2009) and Shidatsu et al. (2011) taken are indicated in the top panel.
using the calculations from Laor (1991) in order to account for relativistic effects from the compact object.

To allow for a difference in PCA and XRT calibrations, we applied a normalization constant to the PCA model and left it free to vary during the fits. All diskbb and powerlaw parameters were left free. The physical reflionx parameters of ionization parameter and iron abundance were left free, but the photon index was fixed to that of the powerlaw component for consistency. The redshift was set to 0 due to the galactic nature of the source, and the normalization was left variable. The kdblur inner radius parameter was left free, the outer radius was assumed to be 400 $R_g$ ($R_g = GM/c^2$), and the disk inclination and emissivity index were varied between separate fitting rounds. As discussed in the introduction, there is a discrepancy between prior results on the inclination $i$ of the binary system. Additionally, the emissivity index $e$, where line emission scales with disk radius as $R^{-e}$, is poorly constrained due to unknown accretion geometry. Recent results indicate varying emissivity indices in black hole accretion disks (Svoboda et al. 2012; Wilkins & Fabian 2012), but kdblur does not incorporate a varying emissivity index. We carried out a total of six rounds of fitting using $i = 20^\circ, 50^\circ$ and $e = 2.1, 3.0, 4.0$. The lower $e$ value of 2.1 was chosen to avoid flux divergence at 2.0, and the upper $e$ value of 4.0 was chosen to investigate values higher than the Newtonian value of 3.0.

Miller et al. (2009) used Chandra High Energy Transmission Grating spectra to show that individual absorption edge column densities remained constant despite state transitions in several BHBs, motivating a fixed hydrogen column density. Thus, all fits were repeated after the hydrogen column density was fixed to a best-fit constant of $7.91 \times 10^{21}$ cm$^{-2}$ based on initial fits. Additionally, the diskbb component was not required in any of the fits to observation 6. Characteristic energy spectra for observation 1 are shown in Figures 3 ($i = 20^\circ$, $e = 3.0$) and 4 ($i = 50^\circ$, $e = 3.0$). Spectral parameters of all seven observations for the $i = 20^\circ$, $e = 3.0$ fitting round are shown in Table 2. The rows give, in descending order, the inner disk temperature, diskbb normalization, kdblur inner radius, photon index,
power-law normalization, iron abundance, reflonx ionization parameter, reflonx normalization, best-fit $\chi^2$, and model luminosity.

3.2. Inner Radius Determination

Inner radii were determined from the kdblur $R_{\text{in}}$ parameter and by using the radial dependence of the diskbb normalization parameter. The normalization parameter is defined as $\sqrt{N_{\text{DBB}}/\cos i} = r_{\text{in}}(\text{km})/d(10\text{kpc})$, where $i$ is the inclination of the disk, $r_{\text{in}}$ is the inner radius, and $d$ is the distance to the object. Physical radii obtained from $N_{\text{DBB}}$ must be converted into units of gravitational radii. We assume a distance of 8 kpc for convenient comparison to prior studies. The inclination was taken to be either 20° or 50° depending on the fitting round. In order to derive a physical inner radius, correction factors due to general relativistic boundary conditions and spectral hardening must be taken into account. Based on Kubota et al. (1998) and Shimura & Takahara (1995), we write the physical radius as $R_{\text{in}} = \xi r_{\text{in}}^2$, and have adopted a relativistic correction factor $\xi = 0.412$ and a spectral hardening factor $\kappa = 1.7$. Finally, we convert $R_{\text{in}}$ to units of gravitational radii $R_g = GM/c^2$. We take the black hole mass to be $10 M_\odot$, again for the purposes of convenient comparison.

To investigate the evolution of disk radius with luminosity, we calculate luminosities for each observation in units of Eddington luminosity. The Eddington luminosity is estimated using a black hole mass of $10 M_\odot$, and our source luminosity is estimated using the unabsorbed model flux from 1 to 100 keV and a distance of 8 kpc. Inner radii obtained from kdblur are plotted against source luminosity in Figure 5 along with the relevant results from Table 6 of Shidatsu et al. (2011), and those obtained from diskbb are shown in Figure 6. Error bars are 90% confidence limits. All of these results used the same distance and mass assumptions as above to determine luminosity in units of $L_{\text{Edd}}$.

3.3. Correlation Analysis

Two statistical tests were performed on the inner radii obtained from each fitting round in order to quantify the relationship the inner disk radius has with luminosity. First, a one-tailed test was used to determine whether the radii were consistent with a constant. The data were fit to a constant, and the resulting $\chi^2$ value was compared to the $\chi^2$ distribution with the appropriate degrees of freedom (5 for diskbb, 6 for kdblur). A $\chi^2$ value in the upper tail of the distribution led to a rejection of the null hypothesis that the radius was constant. Second,
Figure 5. Inner disk radius obtained from kdblur vs. source luminosity are shown in red. Results from all six fitting rounds are shown along with relevant results from Table 6 of Shidatsu et al. (2011). Blue points are from Tomsick et al. (2008), yellow points are from Shidatsu et al. (2011), teal points are from Done & Diaz Trigo (2010), the green lower limit is from Tomsick et al. (2009), the orange point is from Miller et al. (2006b), and the purple point is from Reis et al. (2008).

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

Table 3

| Fitting Round | kdblur $R_{\mu,\rho}$ | $P$-Value | diskbb $R_{\mu,\rho}$ | $P$-Value | Fe $\rho$ | $P$-Value |
|---------------|------------------------|-----------|------------------------|-----------|-----------|-----------|
| $i = 20, e = 2.1$ | $-0.304 \pm 0.258$ | 0.428 | $-0.425 \pm 0.169$ | 6.23e-13 | $-0.281 \pm 0.143$ | 3.10e-6 |
| $i = 20, e = 3.0$ | $0.645 \pm 0.228$ | 1.41e-11 | $-0.113 \pm 0.101$ | 2.94e-7 | $-0.422 \pm 0.150$ | 3.78e-4 |
| $i = 20, e = 4.0$ | $0.011 \pm 0.381$ | 0.401 | $-0.536 \pm 0.169$ | 2.87e-9 | $-0.343 \pm 0.137$ | 6.72e-8 |
| $i = 50, e = 2.1$ | $-0.429 \pm 0.109$ | 0.0313 | $-0.038 \pm 0.264$ | 0.484 | $-0.092 \pm 0.175$ | 8.00e-5 |
| $i = 50, e = 3.0$ | $-0.537 \pm 0.105$ | 1.01e-9 | $0.112 \pm 0.175$ | 9.47e-3 | $0.255 \pm 0.187$ | 1.42e-8 |
| $i = 50, e = 4.0$ | $-0.404 \pm 0.130$ | 0.203 | $-0.495 \pm 0.173$ | 4.55e-9 | $0.084 \pm 0.170$ | 7.26e-9 |

The Pearson correlation coefficient distribution was simulated to determine how the radius depended on luminosity. For each observation and fitting round, $10^5$ inner radii were generated based on the asymmetric 90% confidence regions and assuming Gaussian statistics. From this Monte Carlo generated data, $10^5$ Pearson correlation coefficients were calculated and binned into a histogram. Because it was noticed that the iron abundance has a large variation in all of the fitting rounds, these tests were also carried out on the iron abundance parameter. The $P$-value for rejection of the null hypotheses and the average correlation coefficients ($\rho$) with standard deviations for each fitting round are given in Table 3. To be clear, a low $P$-value is cause to reject the hypothesis of a constant parameter. Plots of the correlation coefficient distributions are shown in Figure 7.

4. DISCUSSION

The inner radii obtained from the kdblur component depend strongly on the assumed disk geometry. It is clear from Figure 5 that there is a general lack of correlation of the inner radii from our various fitting rounds. We attribute this to insufficient energy resolution and/or count rates to reliably distinguish between...
Compton/thermal broadening in reflionx and relativistic broadening in kdblur. Because of this, it is difficult to draw conclusions about the inner radius evolution based on the kdblur $R_{in}$ parameter without independent constraints on the inner disk geometry. While the Pearson correlation coefficient distributions based on kdblur $R_{in}$ shown in Figure 7 for $i = 50^\circ$ (top left) show strong negative correlation between inner radius and luminosity, suggestive of the beginnings of disk recession, only the $i = 50^\circ, e = 3.0$ fitting round has a $P$-value inconsistent with a constant radius (see Table 3). The distributions obtained for $i = 20^\circ$ (middle left) are clearly ambiguous, and only the $i = 20^\circ, e = 3.0$ fitting round has a $P$-value inconsistent with a constant radius.

The kdblur component does have a minor effect on modeling of the thermal disk emission, as can be seen from the energy spectra in Figures 3 and 4. At $i = 20^\circ$, the reduced Doppler broadening from kdblur is compensated by thermal broadening, resulting in a higher reflionx ionization parameter. A higher ionization parameter increases the overall strength of the reflection component and necessitates a smaller reflionx normalization. The stronger reflection at soft energies then suppresses the diskbb component by lowering its normalization, though in observation 5 the inner temperature is driven low instead.

The dependence of inner radii obtained from diskbb on assumed disk geometry is much weaker. Our results shown in Figure 6 show a similar functional form of inner radius between the fitting rounds. Note, however, the higher radius of observation 7 at $i = 50^\circ$ due to the effect of kdblur described above. Because this observation occurs at the highest luminosity ($5.21\% L_{Edd}$), it has a high impact on the correlation distributions and causes the $i = 50^\circ, e = 2.1$ and $i = 50^\circ, e = 3.0$ fitting rounds to be consistent with a constant radius. The other four fitting rounds, all three $i = 20^\circ$ rounds in particular, have $P$-values highly inconsistent with a constant radius and are negatively correlated at $\gtrsim 99.9\%$ confidence (none of the 1000 simulated $\rho$ were positive for these three cases). Thus, our results at $i = 20^\circ$ based on diskbb would constitute strong evidence of a mildly receding inner disk with independent inclination constraints.

The $P$-values in Table 3 all indicate a varying iron abundance. The strength of an iron emission line depends on the amount of iron in the source, but also on how that iron is illuminated (i.e., strength and incidence angle of the illuminating flux). Relativistic effects at the inner disk could produce a wide range of illumination geometries, including a varying emissivity index as pointed out in Section 3.1. Indeed, Bhayani & Nandra (2010) have investigated the variability of relativistic iron lines in

![Figure 6.](image-url)
Seyfert galaxies using rms spectra, and frequently find enhanced variability with respect to the continuum in the red wings of iron lines that are thought to originate at the inner disk. The reflonx model does not account for a varying emissivity index, meaning our varying iron abundance could actually be indicating a change in this geometry. The iron abundances obtained in the $i = 20^\circ$ fits are negatively correlated with luminosity, a phenomenon discovered in Seyferts by Nandra et al. (1997). This monotonic relationship of iron abundance is consistent with the change in disk geometry suggested by our $i = 20^\circ$ diskbb inner radii. Nandra et al. (1997) suggest a more ionized disk at higher luminosities to explain this relationship, though our reflonx ionization parameter shows no signs of positive correlation with luminosity. At $i = 50^\circ$, the relationship of iron abundance with luminosity is weakly and ambiguously correlated.

If the inner disk inclination of GX 339-4 could be independently constrained to $\sim 20^\circ$, our results would imply a truncated disk at lower luminosities. However, none of our results are consistent with an inner radius at the hundreds of gravitational radii suggested by the ADAF model. Previous results at 0.14% $L_{\text{Edd}}$ clearly indicate a significantly truncated disk, so we may have evidence of the beginning of the transition to an ADAF. In this case, a more dramatic dependence of inner radius on luminosity is expected at $\lesssim 0.4% L_{\text{Edd}}$. More observations between 0.1% and 1.0% $L_{\text{Edd}}$ are required to fully understand the inner radius evolution. If relativistic broadening is used to measure the inner radius, thermal broadening must be taken into account and the energy resolution of the observations must be good enough to separate the two broadening mechanisms. If thermal disk modeling is used, deep observations with energy coverage well below 3 keV are required to constrain the shape of the soft
spectral component. In either case, the observations must have excellent statistics in order to provide robust measurements.

The authors thank the anonymous referee for thoughtful criticisms which have improved this work. Ryan Allured and Philip Kaaret acknowledge partial support from NASA grant NNX08AY58G. John A. Tomsick acknowledges partial support from NASA Swift Guest Investigator grants NNX10AF94G and NNX10AK36G.

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