A PROMINENT ACCRETION DISK IN THE LOW-HARD STATE OF THE BLACK HOLE CANDIDATE SWIFT J1753.5−0127

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ABSTRACT

We report on simultaneous XMM-Newton and RXTE observations of the stellar mass black hole candidate SWIFT J1753.5−0127. The source was observed in the “low-hard” state, during the decline of a hard outburst. The inner accretion disk is commonly assumed to be radially truncated in the low-hard state, and it has been suggested that this property may be tied to the production of steady, compact jets. Fits to the X-ray spectra of SWIFT J1753.5−0127 with a number of simple models clearly reveal a cool (kT ≈ 0.2 keV) accretion disk. The disk component is required at more than the 8 σ level of confidence. Although estimates of inner disk radii based on continuum spectroscopy are subject to considerable uncertainty, fits with a number of models suggest that the disk is observed at or close to the innermost stable circular orbit. Recently, an observation of GX 339−4 revealed a disk extending to the innermost stable circular orbit at L/L_Edd ≈ 0.05; our results from SWIFT J1753.5−0127 may extend this finding down to L/L_Edd ≈ 0.003(d/8.5 kpc)^2(M/10 M☉). We discuss our results within the context of low-luminosity accretion flow models and disk-jet connections.

Subject headings: accretion, accretion disks — black hole physics — relativity — stars: individual (SWIFT J1753.5−0127) — X-rays: binaries

1. INTRODUCTION

Stellar mass black holes accreting at or below 10^{-2}L_Edd are found in the “low-hard” state (McClintock & Remillard 2006). This state is typified by a hard power-law X-ray spectrum (Γ ≈ 1.4−1.7), band-limited X-ray noise, high fractional variability (sometimes low-frequency quasi-periodic oscillations, or QPOs, are observed), and steady jet production that has been imaged in at least one case (for reviews, see McClintock & Remillard 2006 and Fender 2006). Recently, a deep observation of GX 339−4 was obtained in the low-hard state (L/L_Edd ≈ 0.05), using XMM-Newton and the Rossi X-Ray Timing Explorer (RXTE; Miller et al. 2006). The properties of the thermal emission from the accretion disk and the width of a relativistic Fe K emission line reveal that the inner disk in GX 339−4 is likely not radially truncated, in contrast to some models for the inner accretion flow and jet production in this regime. The moderate column density along the line of sight to GX 339−4 (N_H ≈ 4 × 10^{21} cm^{-2}) enabled us to study disk emission below 1–2 keV.

SWIFT J1753.5−0127 was discovered in hard X-rays with the Swift Burst Alert Telescope on 2005 May 30 (Palmer et al. 2005). The source was also clearly detected in soft X-rays with the Swift X-ray Telescope (XRT) and in UV with the UV/Optical Telescope (Morris et al. 2005; Still et al. 2005). Optical monitoring of SWIFT J1753.5−0127 revealed a double-peaked Hα emission line, characteristic of the outer accretion disk in X-ray binaries with a low-mass companion star (Torres et al. 2005). At present, the spectral type of the companion and the parameters of the binary (e.g., orbital period, constituent masses, inclination) are not known.

The hard power-law spectrum observed with the Swift/XRT (Morris et al. 2005) and the detection of a 0.6 Hz QPO in pointed RXTE observations are characteristic of the low-hard state (Morgan et al. 2005). SWIFT J1753.5−0127 was detected in radio observations made with MERLIN at a flux density of 2.1 mJy at 1.7 GHz (Fender et al. 2005), likely indicating compact jet activity. Some black hole outbursts do not progress out of the low-hard state (see, e.g., Brocklehurst et al. 2004); public light curves and hardness curves from the RXTE All-Sky Monitor and pointed RXTE observations indicate that SWIFT J1753.5−0127 has remained in this state throughout its outburst. The initial part of the outburst followed a fast rise, exponential decay profile over approximately 100 days, peaking at 0.2 crab. Thereafter, the source has been persistently active at a low flux level (approximately 15 mcrab).

To test whether or not the results from GX 339−4 hold at lower factions of the Eddington limit, we requested a joint XMM-Newton and RXTE observation of the stellar mass black hole candidate SWIFT J1753.5−0127. Similar to GX 339−4, the moderate column density to this source (1.7 × 10^{21} cm^{-2}; Dickey & Lockman 1990) makes it an excellent target for such a study. In the sections that follow, we detail fits made to the XMM-Newton and RXTE spectra of SWIFT J1753.5−0127 in the low-hard state, compare these results to those obtained for GX 339−4, and discuss implications for accretion onto stellar mass black holes.

2. OBSERVATIONS AND DATA REDUCTION

XMM-Newton observed SWIFT J1753.5−0127 on 2006 March 24. The EPIC-pn exposure started at 16:00:31 UT and lasted 42 ks. The camera was operated in “timing” mode, and the “medium” optical blocking filter was used for this observation. We reduced the EPIC data from the ODF level using SAS version 6.5.0 and the latest calibration files. An EPIC-pn event list was obtained by running the processing task epproc. We then screened the pn data to exclude bad events, bad pixels, and events registered too close to chip gaps by requiring “FLAG = 0” and “PATTERN ≤ 4.” Inspection of light curves made from the data revealed no evidence of background flaring, and the entire 42 ks was used to generate EPIC-pn spectra. Source and background spectra were made in the standard way

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by grouping PI channels 0–20479 by a factor of 5. The source spectrum was extracted between 20 and 56 in RAWX, and using the full RAWY range. An adjacent background region was extracted, and the spectra were properly normalized. Custom redistribution matrix files (RMFs) and ancillary response files (ARFs) for the spectra were made using the SAS tasks rmfgen and arfgen. We also made MOS-1 and MOS-2 event lists and spectra. The MOS-1 camera was operated in “full-frame” mode and therefore suffered photon timing mode, which is seldom used. The MOS-2 camera was operated in “full-frame” mode and therefore suffered photon pileup. While results from both MOS cameras confirm the pn results we report below, we regard them as less reliable and do not consider them in this work.

RXTE observed SWIFT J1753.5–0127 on 2006 March 24, starting at 17:22:24 UT. This observation was reduced using the packages and tools available in HEASOFT version 6.0. After standard screening (e.g., against SAA intervals), net Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) exposures of 2.3 and 0.8 ks were obtained, respectively. PCU-2 is the best calibrated Proportional Counter Unit (PCU) in the RXTE/PCA, and so we extracted “Standard2” events (129 channels covering 2–60 keV, obtained every 16 s) from this PCU. Data from all of the Xe gas layers in PCU-2 were combined. Background spectra were made using FTOOL pccbackest, using the latest “bright source” model. An instrument response file was generated using the tool pcresp. We added 0.6% systematic errors to the full PCU-2 spectrum using FTOOLS grppha (Miller et al. 2006). We reduced “archive” mode data from the HEXTE-B cluster; these data have a time resolution of 32 s and cover the 10.0–250.0 keV band with 61 channels. We extracted source and background files, and generated an instrument response file, using the standard procedures.

All spectra considered in this Letter were grouped to require at least 10 counts per bin using FTOOLS grppha to ensure valid results using \( \chi^2 \) statistical analysis. The spectra were analyzed using XSPEC version 11.3.2 (Arnaud & Dorman 2000). Fits made to the EPIC-pn spectrum were restricted to the 0.5–10.0 keV range by calibration uncertainties. Similarly, fits to the PCU-2 and HEXTE-B spectra were restricted to the 2.8–25.0 and 20.0–100.0 keV bands, respectively. All of the error measurements reported in this work are 90% confidence errors, obtained by allowing all fit parameters to vary simultaneously.

**3. ANALYSIS AND RESULTS**

Using standard FTOOLS, we made fast Fourier transforms of the RXTE light curves of SWIFT J1753.5–0127 taken in PCA event modes. The resulting power spectra show strong, band-limited variability that is typical of the low-hard state in accreting black holes. The rms noise amplitude in the 0.01–100 Hz band is 30%. No QPOs were detected in this observation.

Initial spectral fits were jointly made to the RXTE PCA and HEXTE-B spectra with a simple absorbed power-law model. A normalizing constant was allowed to vary between the spectra, and the column density was fixed at the expected value \( (N_H = 1.7 \times 10^{21} \text{ cm}^{-2}) \). This fit gave a power-law index of \( \Gamma = 1.65(2) \) and was in fact a formally acceptable result: \( \chi^2/\nu = 58.8/76 \) (see Fig. 1). RXTE is not sensitive to variations in low column densities, given that its effective lower energy threshold is 3 keV. We note that variations in the column density as large as a factor of 2 only produced changes in the power-law index within the error range quoted above and also resulted in statistically acceptable fits. The power-law index measured with RXTE, then, is not affected by plausible variations in the absorbing column.

We next made fits to the EPIC-pn spectrum, using a simple power law with the column density fixed at 1.7 \( \times 10^{21} \text{ cm}^{-2} \). This model yielded an unacceptable fit \( (\chi^2/\nu = 4855.2/1903) \) and strong residuals below 3 keV in the data/model ratio. We then allowed the column density to vary; this step yielded an improved but unacceptable fit \( (\chi^2/\nu = 3852.5/1901) \). The addition of a disk component to this model yields significantly improved fits. With the addition of a disk component, the following parameters are obtained: \( \text{Norm}_{\text{disk}} = 1200 \pm 200 \), \( \Gamma = 1.66(1) \) (consistent with RXTE), and \( \text{Norm}_{\text{pow}} = 5.50(5) \times 10^{-2} \) \( \chi^2/\nu = 2227.0/1899 \). The soft excess in this spectrum is shown in Figure 2, and the total fit is shown in Figure 3. The disk component is required at more than the 8 \( \sigma \) level of confidence, as determined by an \( F \)-test. This two-component model gives an unabsorbed flux of \( 3.9 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \) (0.5–10.0 keV) and a luminosity of \( 3.4 \times 10^{38} \text{ ergs s}^{-1} \), \( L_X/L_{\text{edd}} = 2.6 \times 10^{-7} (d/8.5 \text{ kpc})^{-2} (\text{M}/10 \text{M}_\odot)^{-1} \). Of importance is the radius of the inner disk; the normalization gives a radius of 30(5)(d/8.5 kpc)/cos \( i \) km, or 2.0(3)(M/10 M_\odot)(d/8.5 kpc)/(cos i)\( 1/2 \) \( r_g \) (where \( r_g = GM/c^2 \)).
For the disk blackbody radius given above, \( r_{\text{in}} \leq 6GM/c^2 \) for \( i \leq 83^\circ \) at 8.5 kpc and for \( i \leq 87^\circ \) (assuming \( M = 10 M_\odot \)), assuming \( d = 2.9 \) kpc (see below). At such high inclinations, eclipses (not yet reported) would be expected. For inclinations greater than 60\(^\circ\), \( r \geq 6GM/c^2 \) would nominally hold for \( d \geq 18 \) kpc, assuming \( M = 10 M_\odot \), or for \( d \geq 9 \) kpc, assuming \( M = 5 M_\odot \). However, it is likely that SWIFT J1753.5–0127 is closer than 8.5 kpc, making it even more likely that the disk is close to the black hole. Of the 18 dynamically confirmed black hole binaries in the Milky Way, only one may be as distant as 20 kpc (GS 1354–64; Casares et al., 2004), and only one other is more distant than 8.5 kpc (GRS 1915+105; e.g., Zdziarski et al. 2005). Torres et al. (2005) report \( H = 14.8 \) on 2006 July 11. On that day, an observation with the RXTE/PCA gives a flux of \( 4.3 \times 10^{-9} \) ergs s\(^{-1}\) (2.8–12.0 keV), assuming a \( \Gamma = 1.7 \) power-law spectrum.Russel et al. (2006) have recently found an empirical relation between optical/IR luminosity and X-ray luminosity: \( L_{\text{opt}} = 10^{13}(L_X)^{0.61} \). Given the observed fluxes and a reddening of 0.19 for \( N_H = 1.7 \times 10^{21} \) cm\(^{-2}\), this relation implies a distance of 2.9 kpc to SWIFT J1753.5–0127. Thus, the fit above implies that the accretion disk in SWIFT J1753.5–0127 is likely sitting at or near to the innermost stable circular orbit (ISCO), for a broad range of system parameters.

Apart from uncertainties in distance, black hole mass, and inclination, the choice of hard component model, disk model, and radiative transfer through a disk atmosphere can all act to distort the observed disk parameters. For instance, Zimmerman et al. (2005) show that enforcing a zero-torque inner boundary condition can drive estimates of the inner radius values smaller by a factor of \( \sim 2 \), relative to the diskbb model. Shimura & Takahara (1995) suggest that radiative transfer may act to give an inferred inner disk radius that is too small by a factor of \( \sim 3 \); Merloni et al. (2000) suggest this factor may be as high as \( \sim 9 \) in some cases. Torque conditions and radiative transfer may partially cancel out, but they represent important additional uncertainties.

In order to establish the nature of the disk as robustly as possible, we jointly fit the EPIC-pn, PCA-2, and HEXTE-B spectra with several continuum models. For each model fit to the data, an overall normalizing constant was allowed to float between the spectra. We employed three different disk models: “diskbb” (which assumes maximal inner torque), “ezdiskbb” (which assumes zero inner torque), and “diskpn” (which assumes zero inner torque and a pseudo-Newtonian inner potential). For each disk model, we employed three different models for the hard component: a simple power law, a hot optically thin Comptonizing corona, and a cool optically thick Comptonizing corona. The parameters obtained with these models are listed in Table 1. Each of these models suggests that the disk in SWIFT J1753.5–0127 extended close to the ISCO during our observations, for plausible ranges of source distance, inner disk inclination, and black hole mass. The implication that the disk extends close to the black hole in SWIFT J1753.5–0127 is not strongly model-dependent. It is important to note that the models with a low coronal electron temperature are significantly worse than the others; they fail to produce the hard flux required to fit the HEXTE-B spectrum.

If we assume that a disk temperature of \( kT \approx 1.0–2.0 \) keV is typical for a stellar mass black hole accreting at its Eddington limit (e.g., McClintock & Remillard 2006), the range of temperatures implied by our fits is consistent with the theoretical expectation that \( T \propto M^{3/4} \) in standard disks around black holes (see, e.g., Frank et al. 2002). This theoretical consistency in-

![Fig. 3.—EPIC-pn spectrum of SWIFT J1753.5–0127, fit with a simple absorbed disk blackbody plus power-law model (see Table 1). A number of variations on this spectrum produce acceptable fits and demonstrate that the requirement of a disk that extends to the ISCO in SWIFT J1753.5–0127 is not strongly model-dependent.](image-url)

### TABLE 1

| Model/Parameter | \( N_H \) (10\(^{22}\) cm\(^{-2}\)) | \( kT \) (keV) | \( r_{\text{in}} \) (\( r_g \)) | \( \Gamma \) | \( kT_e \) (keV) | \( \tau \) | Norm. | \( \chi^2/\nu \) |
|-----------------|------------------|-------------|----------------|-----|-------------|-----|------|-------------|
| diskbb+pow ........... | 2.3(1) | 0.23(1) | 1.9(2) | 1.66(1) | ... | ... | 5.5(5) | 10 \(^{-2}\) | 2286/1976 |
| ezdiskbb+pow ........... | 2.3(1) | 0.21(2) | 2.5(3) | 1.66(1) | ... | ... | 5.5(5) | 10 \(^{-2}\) | 2290/1976 |
| diskpn+pow ........... | 2.3(1) | 0.21(1) | 6.0 | 1.66(1) | ... | ... | 5.5(5) | 10 \(^{-2}\) | 2290/1976 |
| diskbb+compt ........... | 1.6(1) | 0.18(1) | 2.4(4) | ... | 50.0 | 1.03(1) | 3.1(1) | 10 \(^{-3}\) | 2158/1976 |
| ezdiskbb+compt ........... | 1.7(1) | 0.17(1) | 3.0(4) | ... | 50.0 | 1.03(1) | 3.1(1) | 10 \(^{-3}\) | 2159/1976 |
| diskpn+compt ........... | 1.7(1) | 0.17(1) | 6.0 | ... | 50.0 | 1.03(1) | 3.0(1) | 10 \(^{-3}\) | 2159/1976 |
| diskbb+compt ........... | 1.7(1) | 0.16(1) | 2.2(5) | ... | 5.0 | 5.1(1) | 3.2(1) | 10 \(^{-2}\) | 2562/1976 |
| diskbb+compt ........... | 1.7(1) | 0.16(1) | 3.0(5) | ... | 5.0 | 5.1(1) | 3.2(1) | 10 \(^{-2}\) | 2566/1976 |
| diskbb+compt ........... | 1.7(1) | 0.16(1) | 6.0 | ... | 5.0 | 5.1(1) | 3.2(1) | 10 \(^{-2}\) | 2566/1976 |

Notes.—The results of jointly fitting simple models to the XMM-Newton/EPIC-pn and RXTE PCA and HEXTE spectra of SWIFT J1753.5–0127 are given above. Each of the above models was modified by interstellar absorption using the “phabs” model. An overall normalizing constant was allowed to float between the spectra. The electron temperature and optical depth in the “compt” model could not be constrained, so two extremes are examined above. In both cases, the electron temperature of the corona is fixed at the quoted value. Radii derived from the “diskbb” and “ezdiskbb” models are given in terms of \( f_i(\theta, \delta) \) kpc/\( M_\odot \), where \( f_i \) is the spectral hardening factor and \( i \) is the inner disk inclination (the “diskbb” model assumes \( f_i = 1 \), and the “ezdiskbb” model assumes \( f_i = 1.7 \)). Fits made with the “diskpn” disk model were made with the radius fixed at 6\( r_g \), as suggested by the XSPEC notes on this model.
dicates that the observed soft component is a simple accretion disk continuum spectrum.

An independent observational constraint on the inner disk radius would have been possible, if a strong relativistic Fe K emission line like that in GX 339−4 had been detected. For a broad range of disk inclinations, a relativistic “Laor” line consistent with moderate black hole spin with an equivalent width of 60 eV cannot be ruled out. This line strength would correspond to a reflection fraction of 0.3 for a disk with low ionization (George & Fabian 1991), comparable to the reflection constraints reported in stellar mass black holes in brighter phases of the low-hard state (e.g., Miller et al. 2006). A strong line (200−300 eV) like that detected in GX 339−4 (Miller et al. 2006) is ruled out in SWIFT J1753.5−0127.

4. DISCUSSION AND CONCLUSIONS

Spectral and timing analyses of SWIFT J1753.5−0127 reveal that the source was in the low-hard state when observed simultaneously with XMM-Newton and RXTE in 2006 March. Fits to the XMM-Newton EPIC-pn spectrum reveal clear evidence of an accretion disk that likely extends close to the ISCO around the black hole. This result confirms prior results based on an XMM-Newton and RXTE observations of the stellar mass black hole GX 339−4 (Miller et al. 2006) and ASCA observations of Cygnus X-1 (Miller et al. 2006; also see Ebisawa et al. 1996 and Balucinska & Hasinger 1991), and likely extends those findings down an order of magnitude in fractional Eddington luminosity, to $L_{\chi}/L_{Edd} = 2.6 \times 10^{-3} (d/8.5 \text{ kpc})^2 (M/10 M_\odot)$. Whereas GX 339−4 was observed in a low-hard state during the rising phase of its 2004 outburst, we observed SWIFT J1753.5−0127 during the decay phase of its 2005−2006 outburst. It follows, then, that disks can remain close to the ISCO in the low-hard state in both the rising and decay phases of an outburst.

Advection-dominated accretion flow models (e.g. Esin et al. 1997) predict that the inner disk should be radially truncated in the low-hard state. Indeed, in some black holes observed at similar fractions of the Eddington limit (e.g., XTE J1118+480; McClintock et al. 2001) and at lower luminosities, it is possible that the disk may be radially recessed. However, our results suggest that this prediction may not hold universally in the low-hard state. A phenomenological model for jet production (Fender et al. 2004) suggests that a truncated disk may facilitate jet production, in part because jet production does appear to be largely quenched in “high-soft” states of stellar mass black holes (Fender 2006) wherein the inner disk is commonly thought to extend close to the black hole. Our observation of SWIFT J1753.5−0127 suggests that the jet production may not be enabled by a radially truncated disk or quenched by a filled innermost accretion disk. Other factors, perhaps including the mass accretion rate, or the absence of a strong corona in high-soft states, may inhibit jet production.

As previously noted, the spectral results obtained from this analysis are not necessarily at odds with inferences drawn from X-ray timing analyses of black holes in the low-hard state (Miller et al. 2006). Low-frequency QPOs and noise components are not likely to be directly related to Keplerian orbital frequencies at the ISCO. In transitions from the low-hard states to higher flux states, the frequency of low-frequency QPOs are sometimes observed to saturate. Again, however, this is not necessarily indicative of the ISCO, as such QPOs have been observed simultaneously with high-frequency QPOs that are plausibly related to Keplerian orbits in the inner disk (Remillard et al. 2002).

On theoretical grounds, it is all but impossible that a standard optically thick accretion disk can remain near the black hole in the least luminous phases of the low-hard state as the source approaches quiescence. However, the fraction of the Eddington luminosity at which the disk is actually truncated is yet to be determined. Exploring the regime near $L_{\chi}/L_{Edd} \approx 10^{-4}$ will require an order of magnitude longer observation than this 43 ks exposure. Similarly, obtaining confirmation of the disk radius at $L_{\chi}/L_{Edd} \approx 10^{-3}$ via the width of an Fe K emission line would likely also require a 400−500 ks observation.

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