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MODELING THE ACCRETION DISK X-RAY CONTINUUM OF BLACK HOLE CANDIDATES

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ABSTRACT

We critically examine issues associated with determining the fundamental properties of the black hole and the surrounding accretion disk in an X-ray binary based on modeling the disk X-ray continuum of the source. We base our work mainly on two *XMM-Newton* observations of GX 339–4, because they provided high-quality data at low energies (below 1 keV), which are critical for reliably modeling the spectrum of the accretion disk. A key issue examined is the determination of the so-called “color correction factor,” which is often empirically introduced to account for the deviation of the local disk spectrum from a blackbody (due to electron scattering). This factor cannot be predetermined theoretically, because it may vary with, e.g., mass accretion rate, among a number of important factors. We follow up on an earlier suggestion to estimate the color correction observationally by modeling the disk spectrum with saturated Compton scattering. We show that the spectra can be fitted well, and the approach yields reasonable values for the color correction factor. For comparison, we have also attempted to fit the spectra with other models. We show that even the high-soft state continuum (which is dominated by the disk emission) cannot be satisfactorily fitted by state-of-the-art disk models. We discuss the implications of these results.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (GX 339–4) — X-rays: stars

Online material: color figures

1. INTRODUCTION

The X-ray continuum of black hole candidates (BHCs) is roughly composed of two main elements (see review by Liang 1998), an ultrasoft component that is thought to be associated with emission from the accretion disk, and a hard component that is thought to be produced by inverse Compton scattering of soft photons by energetic electrons that can be either thermal or nonthermal in origin. Modeling the disk component could, in principle, allow one to determine the radius of the inner edge of the accretion disk in a BHC (review by Tanaka & Lewin 1995, and references therein). This has been tried, and the results have provided evidence that the accretion disk extends all the way in to the last stable orbit under certain circumstances (Tanaka & Lewin 1995). Motivated by this observation, Zhang et al. (1997) suggested that modeling the X-ray continuum of a BHC could lead to a measurement of the spin of the black hole, if the mass of the black hole can be independently derived.

In retrospect, we now know that the accretion disk reaches the last stable orbit probably only in the high-soft state (e.g., Narayan 1996),¹ so the proposed technique may only be applicable to data taken in such a state. Since the X-ray spectrum of BHCs is dominated by the disk component in the high-soft state, the determination of the disk parameters based on spectral modeling should, in principle, be quite accurate, even if one neglects the hard component, whose physical origin is less well understood, particularly in

the high-soft state. However, there are still serious issues associated with the exercise.

First, the local spectrum of the X-ray emitting portion of the accretion disk is not a blackbody, because the opacity is dominated by electron scattering. Saturated Comptonization leads to a “diluted” blackbody spectrum, whose color temperature is given by $T_{\text{col}} = f_{\text{col}} T_{\text{eff}}$, where f_{col} is the color correction factor, and T_{eff} is the effective temperature (Ebisuzaki et al. 1984). Much effort has gone into finding the values of f_{col} that are appropriate for BHCs (Shimura & Takahara 1995; Merloni et al. 2000; Davis et al. 2006). The situation is still uncertain, but it is clear that f_{col} depends on a number of important physical parameters, such as mass accretion rate, which can vary even for a given source. It is, therefore, not possible to know what value to use a priori. Cui et al. (2002) proposed an observational approach to derive f_{col} from the data (see also Shrader & Titarchuk 1999). Although the technique showed some promise with limited data, it needs to be tested further.

Second, there is observational evidence (Zhang et al. 2000) that the surface layer of the accretion disk in BHCs might deviate from the standard α -disk structure (Shakura & Sunyaev 1973). Such an effect is expected from X-ray heating of the disk by a central hard X-ray source (e.g., Nayakshin & Melia 1997; Mistrá et al. 1998), but it is not clear why the effect is still significant even for the high-soft state, in which hard X-ray production is expected to be quite weak. The presence of such a “warm” layer would add further complication in modeling the observed X-ray spectrum (Zhang et al. 2000), because Compton scattering in the layer can further modify the spectrum.

Third, some of the widely used disk models (e.g., the multicolor disk; Mitsuda et al. 1984) do not take into account general relativistic effects that can affect the formation of the X-ray spectrum. Attempts have been made to incorporate the effects empirically in the analysis by introducing a number of correction factors (Zhang et al. 1997). Recently, two new disk models have been developed

¹ It has recently been argued, based on hard-state observations of BHCs (e.g., Miller et al. 2006), that the disk also reaches the last stable orbit in the low-hard state. We must, however, caution against drawing strong conclusions on the properties of the disk from modeling a hard-state spectrum, because it would require a reliable extraction of the weak disk component from the dominating hard component, whose precise origin (e.g., the geometry of the emitting region and the source of seed photons) is still being debated (see Cui et al. 2002 for an in-depth discussion). This is why we chose to focus on the soft-state observations in this work.

that account for the general relativistic effects (Li et al. 2005; Davis & Hubeny 2006). The models also consider spectral hardening due to scattering, with one treating f_{col} as a free parameter (Li et al. 2005), and the other carrying out radiative transfer in the disk (Davis & Hubeny 2006). The models have been applied to observations of a number of BHCs (Shafee et al. 2006; Davis et al. 2006; McClintock et al. 2006; Middleton et al. 2006).

In this work, we examined some of the issues and also assessed the viability of the state-of-the-art disk models, making use of data of much improved quality that have recently become available. Specifically, we analyzed two *XMM-Newton* observations of GX 339–4 and attempted to fit the observed X-ray spectra with different models. With its large effective area and good sensitivity at low energies (<1 keV), *XMM-Newton* offers distinct advantages over other X-ray observatories for our purposes. The low-energy sensitivity is often not appreciated as much as it should be; it is critical to reliable modeling of the disk spectrum, because the effective temperature of the disk is typically $\lesssim 1$ keV for BHCs.

2. DATA

2.1. *XMM-Newton* Observations

We analyzed data from two archival *XMM-Newton* observations (ObsIDs 0093562701 and 0148220201) of GX 339–4 during its 2002–2003 outburst. The first observation was taken near the peak of the outburst (on 2002 August 24), judging from the *ASM/RXTE* light curve,² while the second one was taken at the tail end of the episode (on 2003 March 8). GX 339–4 was observed for about 61 and 20 ks during the two observations, respectively. Since we are mainly interested in the X-ray continuum here, we focused on the EPIC data. The pn/EPIC detector was operated in the burst mode, with the thin optical blocking filter, during the first observation, and the MOS/EPIC detectors were not used. In the second observation, the pn and MOS detectors were both run in the timing mode with the medium blocking filter. Even with the timing mode, the MOS data still suffer from severe photon pile-up due to the high count rate. In contrast, the pile-up effects are minimal in the pn data. This work is, therefore, based on the pn data.

The data were reduced with the standard SAS package (version 7.0.0). We followed the procedures described in the *XMM-Newton* data analysis cookbook³ in preparing and filtering the data, making light curves, extracting spectra, and generating the corresponding ARF and RMF files for subsequent spectral modeling. We did need to turn off the bad-pixel search in processing the first observation because of a bug in the searching routine for the burst mode. The effects should be negligible, because the source was very bright then. The events of interest were extracted from a rectangular region, with RAWX 32–40 RAWY 3–179 and RAWX 34–42 RAWY 3–199 for the 2002 and 2003 observations, respectively. Filtering expressions “FLAG = 0” and “PATTERN ≤ 4 ” were applied to select good single and double events.

Because the source was bright during both observations, a significant number of source events are present even near the edge of the CCD chip, which makes it impossible to cleanly extract background events. This should only affect the high-energy end of the spectrum (where the background counts may become comparable or exceed the source counts). Our choice of the central 9 columns of the chip was made to minimize the effect on the shape of the spectrum. However, it led to an underestimation of the over-

all normalization, which is also important here. To determine the normalization more accurately, we also made spectra with events from the whole chip. The difference amounts to roughly 8%. For spectral modeling, we added a 1% systematic error to the data and grouped the channels so that each bin contains at least 500 counts.

2.2. *RXTE* Observations

To complement the soft-band coverage of *XMM-Newton*, we obtained simultaneous *RXTE* data from the public archive. GX 339–4 was observed with *RXTE* for about 4 and 16 ks, respectively, during the two *XMM-Newton* observing periods. The data were reduced with FTOOLS 5.2. We followed the standard steps⁴ in preparing and filtering the data, deriving PCA and HEXTE spectra from data taken in the standard modes, and generating the corresponding response files for spectral modeling.

A PCA or HEXTE spectrum consists of separate spectra from the individual detector units that were in operation. In deriving the PCA spectra, we only used data from the first xenon layer of each detector unit (which is best calibrated) and combined spectra from all the live detectors into one to maximize the signal-to-noise ratio (S/N). To estimate the PCA background, we used the background model for bright sources (pca_bkgd_cmbrigtvle_eMv20030330.md1). As for the HEXTE data, we extracted a spectrum for each of the two clusters separately. For spectral modeling, we rebinned the HEXTE spectra, so that each bin contains at least 5000 counts. We also added a 1% systematic error to both the PCA and HEXTE spectra.

3. RESULTS

We carried out spectral modeling in XSPEC (Arnaud 1996). The spectral bands of interest are 0.5–10 keV (pn/EPIC), 3–25 keV (PCA), and >15 keV (HEXTE). The spectra are always jointly fitted with a common model, except for a normalization factor (fixed at unity for the pn data) that was introduced to account for any residual difference in the calibration of the throughput of the detectors. Strictly speaking, however, the *XMM-Newton* and *RXTE* coverages are not always simultaneous, due to the difference not only in the observing time but also in the orbits of the two satellites. To justify joint modeling, we broke each of the *XMM-Newton* observations into eight segments and extracted a spectrum for each segment. We compared the individual spectra and observed no apparent variation in the shape of the spectrum in either case.

We experimented with several models for the ultrasoft and hard components of the spectrum. The former is often modeled with a nonrelativistic, multitemperature blackbody model (diskbb in XSPEC; Mitsuda et al. 1984). For this work, we instead used the two relativistic disk models (kerrbb in XSPEC, Li et al. 2005; and bhspec, Davis & Hubeny 2006). To test the procedure of deriving the color correction factor from the data, as proposed by Cui et al. (2002), we also modeled the disk component with saturated Compton scattering (comptt in XSPEC, in a disk geometry; Titarchuk 1994). In all cases, the hard component of the spectrum was modeled with unsaturated Compton scattering (also comptt but in a spherical geometry). Interstellar absorption was taken into account (with phabs in XSPEC).

The best and only formally acceptable fit to the continuum was obtained with comptt+comptt. In this case, the residuals reveal the presence of discrete features, which include absorption edges at 863 and 880 eV for the 2002 and 2003 observations, respectively, and emission lines at 569 and 562 eV. We suspect that the

² See http://heasarc.gsfc.nasa.gov/xte_weather.

³ See <http://wave.xray.mpe.mpg.de/xmm/cookbook>.

⁴ See http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html.

FIG. 1.—Broad line detected in the 2003 X-ray spectrum. Shown are the residuals after the 1aor component is removed from the best-fit model (see text).

edges are calibration artifacts, since we were not able to associate them with any elements. On the other hand, the emission features could be real, with the former being associated with O VIII and the latter with O VII (corresponding to transitions at rest-frame energies 569 and 561 eV, respectively), which would imply a plasma temperature of 0.1–0.2 keV. The lines are unresolved and are quite weak, with equivalent widths of 26 and 21 eV for the 2002 and 2003 observations, respectively. We will not discuss the discrete spectral features any further, since the main focus here is on the X-ray continuum. The 2002 data also show the presence of an emission feature at 2.2 keV, which is likely an artifact caused by calibration uncertainty around the M-edge of gold (in the mirror coating). However, the feature is not apparent in the 2003 data, which is a bit puzzling, because the statistics are comparable in the two cases. We consulted with the *XMM-Newton* Helpdesk about it and were told that it had probably been corrected for by the calibration in the timing mode, but not so well in the burst mode. After accounting for the discrete spectral features (with edge and gaussian in XSPEC), we still saw, in the residuals, genuine inconsistency between the pn/EPIC and PCA data at low energies, which could be related to known PCA calibration uncertainties around the L-edge of xenon. For this work, we resolved the issue simply by excluding the PCA data below 9 keV in the joint fits.

For the 2003 data, the continuum fit also shows significant structures in the residuals roughly in the range of 5–8 keV, which might be similar to those reported by Miller et al. (2004) based on an *XMM-Newton* observation taken several months earlier. They are most likely associated with the K α emission of the iron and its associated absorption edge. The excess appears broad and asymmetric in shape, as illustrated in Figure 1. Therefore, we modeled it as a gravitationally redshifted disk line (1aor in XSPEC; Laor 1991). Also, we included a smeared edge (smedge in XSPEC) in the fit. The results are: $E_{\text{Laor}} = 6.48^{+0.07}_{-0.09}$ keV, $i = 51^{+2}_{-1}$ deg, $q = 5.2 \pm 0.2$, and $R_{\text{in}} = 1.76^{+0.10}_{-0.06} R_g$ (where R_g is the gravitational radius) for the line; $E_{\text{edge}} = 8.5 \pm 0.1$ keV, $W = 2.7^{+0.5}_{-0.4}$ keV, and $\tau = 0.59^{+0.07}_{-0.05}$ for the edge. Note that we fixed R_{out} at $400 R_g$ in the 1aor model. The obtained value for the inclination angle (i) is consistent with those estimated for the system (e.g., Zdziarski et al. 2004). If this interpretation is correct, the results would require a very high value ($a^* \gtrsim 0.97$) for the black hole spin (cf. Miller et al. 2004). However, no such broad line (nor the edge) is apparent in the 2002 data. Adding the line (as a Gaussian component) to the model, we found that the data could accommodate it, but its equivalent width would be merely 14^{+12}_{-9} eV, compared to 485^{+217}_{-130} eV based on the 2003 data.

Figure 2 shows the observed X-ray spectra of GX 339–4, along with the best-fit models and the associated residuals. The parameters of the continuum fits are summarized in Table 1. The source was clearly in the high-soft state during the 2002 observation, with the disk contributing about 96% of the 0.5–10 keV flux. The spectrum became harder during the 2003 observation, but the disk still contributed about 80% of the 0.5–10 keV flux. Following Cui et al. (2002), we attempted to derive the color correction factor from the continuum fits. Briefly, to account for the effects of scattering in a Shakura-Sunyaev disk (Shakura & Sunyaev 1973), one should, strictly speaking, start with a multitemperature blackbody spectrum for the seed photons. However, *comptt* assumes a Wien spectrum for the seed photons. Fitting the peak of *diskbb* with a Wien distribution leads to $T_{\text{diskbb}} = 2.7 T_{\text{Wien}}$. Based on spectral modeling with *comptt*, therefore, we can approximate the color correction factor as $f_{\text{col}} = T_e / 2.7 T_0$ (Cui et al. 2002; see also Zhang 2005). For the 2002 and 2003 observations, respectively, we have $f_{\text{col}} = 1.48^{+0.09}_{-0.08}$ and $1.35^{+0.01}_{-0.01}$, which seem quite reasonable. This lends support to the viability of the observational approach in deriving f_{col} .

We then replaced the saturated Compton component with a multicolor disk model, but failed to obtain any formally acceptable

FIG. 2.—Observed X-ray spectra of GX 339–4 from the 2002 (left) and 2003 (right) observations. The best-fit models are shown in solid histograms. The bottom panels show the respective residuals of the fits. [See the electronic edition of the Journal for a color version of this figure.]

TABLE 1
BEST X-RAY CONTINUUM FITS

OBSERVATION	N_H (10^{21}cm^{-2})	comptt				comptt				χ^2/dof
		kT_0 (keV)	kT_e (keV)	τ	K	kT_0 (keV)	kT_e (keV)	τ	K	
2002.....	4.5(+1 -2)	0.20(1)	0.793(+3 -4)	13.4(2)	25(+2 -1)	1.7(+2 -1)	46 $^{+56}_{-21}$	1.8(+1 -2)	1.7 $^{+1.7}_{-1.4} \times 10^{-3}$	978/1201
2003.....	4.75(1)	0.170(1)	0.618(1)	10.07(2)	7.58(2)	1.11(1)	183(2)	0.38(2)	3.21(3) $\times 10^{-3}$	920/1076

NOTES.—The numbers in parentheses indicate uncertainty in the last digit. For asymmetric errors, both the lower and upper bounds are shown, again for the last digit. The errors shown represent 90% confidence intervals for single parameter estimation.

fits to the observed X-ray continua with either `kerrbb` or `bhspec`. In this case, we fixed the inclination angle at the value from relativistic line modeling (51°), the mass of the black hole at $10 M_\odot$, and the distance at 8 kpc (Zdziarski et al. 2004). With `kerrbb`, we also adopted the default settings for torque-free inner boundary condition, returning radiation, and limb darkening, and fixed the normalization at unity and the color correction factors at the values that we derived. The best-fit models are shown in Figure 3. Neither one is formally acceptable, with $\chi^2/\text{dof} = 2634/1203$ and $2010/1079$ for the 2002 and 2003 observations, respectively. The residuals show significant structures in both cases. Taken at its face value, the black hole spin would be about 0.7, after correcting for the loss of flux due to the use of the central nine columns of the pn chip (see § 2.1). The situation is hardly improved when the inclination angle and the color correction factor are allowed to vary.

Figure 4 shows the best-fit models with `bhspec`. Again, significant features are noticeable in the residuals. The χ^2 values of the fits are $\chi^2/\text{dof} = 2246/1203$ and $2505/1079$ for the 2002 and 2003 observations, respectively. As already mentioned, in this model spectral hardening (due to electron scattering) is taken into account in modeling the disk atmosphere. Again, taken at its face value, the black hole spin is about 0.5. Relaxing the inclination angle does not improve the fits.

4. DISCUSSION

The importance of accurately modeling the accretion disk X-ray continuum of BHCs goes beyond gaining insights into radiative processes associated with accretion flows. It also lies in the exciting prospect of deriving the spin of black holes from such spectral modeling. The technique is one of many that have

been proposed for BHCs (Laor 1991; Bromley et al. 1997; Zhang et al. 1997; Nowak et al. 1997; Cui et al. 1998; Stella et al. 1999; Wagoner et al. 2001; Abramowicz & Kluzniak 2001). Although varying degrees of success have been achieved, it is fair to say that the techniques all have serious issues in their applications to the data. Further investigation, both theoretical and observational, is thus needed to examine the issues.

We have demonstrated in this work that the high quality of the data is starting to demand a proper treatment of electron scattering in radiative transfer through the accretion disk around a stellar-mass black hole. Some of the effects that were not appreciated previously in fitting low S/N data are now becoming apparent. At present, this demanding situation fundamentally limits our ability to reliably derive the physical parameters of the accretion disk or the black hole in an X-ray binary, based on modeling the disk X-ray continuum. There are also observational issues that add additional uncertainties to the exercise. For instance, many key parameters (e.g., black hole mass, inclination angle, and distance) that characterize a source are often poorly determined but are needed to determine, e.g., the black hole spin. This is entirely independent of the quality of X-ray data. Also, perhaps less appreciated are the significant uncertainties in the absolute and cross calibrations of the detectors on different X-ray satellites. This issue is relevant, because the determination of the spin of a black hole in an X-ray binary depends critically on the overall normalization of the X-ray continuum. This is the reason why one must be very careful in comparing results based on data from different satellites.

We have shown that neither of the two state-of-the-art disk models is capable of satisfactorily fitting the observed ultrasoft component of the spectra of GX 339–4. While this is perhaps not

FIG. 3.—Same as Fig. 2, but the disk emission was modeled with `kerrbb`. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 4.—Same as Fig. 2, but the disk emission was modeled with *bhspec*. [See the electronic edition of the *Journal* for a color version of this figure.]

totally surprising for *kerrbb*, since it does not actually carry out radiative transfer calculations, it is for *bhspec*. These models have recently been applied to data to derive the spin of black holes in a number of systems, so our finding is somewhat disappointing. If we take the best-fit parameters at their face values, the models would suggest that GX 339–4 contains a moderately rotating black hole (with $a^* \sim 0.5$ – 0.6). On the other hand, if we attribute the asymmetry in the profile of the observed Fe K α line to gravitational redshift, we would conclude that the source contains a rapidly rotating black hole (with $a^* \approx 0.96$). We should note, however, that the apparent inconsistency can be easily reconciled when we take into account the large uncertainties associated with, e.g., black hole mass, inclination angle, and distance. For example, if we adopt $13.5 M_\odot$ for the black hole mass, 51° for the inclination, and 7.5 kpc for the distance, the *kerrbb* model yields $a^* \approx 0.93$ and 0.96 when fitting the 2002 and 2003 data, respectively.

We were able to fit the ultrasoft component quite satisfactorily with a simple saturated Compton scattering model. The results allowed us to test a procedure that was previously suggested by Cui et al. (2002) to empirically derive the color correction factor from the same X-ray data. The values obtained are very close to the theoretical expectation (e.g., Shimura & Takahara 1995), which is also often adopted in spectral modeling. Therefore, our results have provided further support for this observational approach. Although the use of a single color correction factor ignores possible radial dependence of spectral hardening in the disk, it does not seem unreasonable given that the X-ray emission from the disk originates from a relatively narrow region (closest to the black hole).

5. CONCLUSIONS

Based on our joint spectral analysis of two simultaneous *XMM-Newton*/*RXTE* observations of GX 339–4, we can draw following conclusions:

1. The empirical procedure to derive the color correction factor (f_{col}) observationally, as proposed by Cui et al. (2002), yields reasonable results. If confirmed by further investigations, this would eliminate a major (theoretical) uncertainty in deriving the parameters of the disk from modeling the X-ray continuum.
2. The observed X-ray continuum of GX 339–4 in the high-soft state, which is dominated by emission from the optically thick accretion disk, cannot be satisfactorily fitted by any existing disk model. Therefore, one should exercise caution in assessing quantitative results from such spectral modeling.

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