TESTING ACCRETION DISK STRUCTURE WITH SUZAKU DATA OF LMC X-3

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Received 2009 November 19; accepted 2010 March 15; published 2010 April 15

ABSTRACT

The Suzaku observation of LMC X-3 gives the best data to date on the shape of the accretion disk spectrum. This is due to the combination of very low absorbing column density along this line of sight, which allows the shape of the disk emission to be constrained at low energies by the CCDs while the tail can be simultaneously determined up to 30 keV by the high-energy detectors. These data clearly demonstrate that the observed disk spectrum is broader than a simple “sum of blackbodies,” and relativistic smearing of the emission is strongly required. However, the intrinsic emission should be more complex than a (color-corrected) sum of blackbodies as it should also contain photoelectric absorption edges from the partially ionized disk photosphere. These are broadened by the relativistic smearing, but the models predict ∼3%–5% deviations for 1/3–1 solar abundance around the edge energies, significantly stronger than observed. This indicates that the models need to include more physical processes such as self-irradiation, bound–bound (line) absorption, and/or emission from recombination continua and/or lines. Alternatively, if none of these match the data, it may instead require that the accretion disk density and/or emissivity profile with height is different to that assumed. Thus, these data demonstrate the feasibility of observational tests of our fundamental understanding of the vertical structure of accretion disks.

Key words: accretion, accretion disks – black hole physics – stars: individual (LMC X-3) – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

It is important to study the emission from the accretion disk to understand how the gravitational energy is converted to radiation. The simplest models of accretion disk spectra assume that the gravitational energy dissipated at each radius thermalizes to a blackbody spectrum. Summing it over all radii, under an appropriate inner boundary condition, produces the well-known Shakura & Sunyaev (1973) disk model. This is derived in Newtonian gravity, but was extended to full general relativity by Novikov & Thorne (1973). The maximum temperature produced by a disk accreting close to the Eddington limit around a 10 M⊙ black hole is 1–2 keV, easily observable with X-ray satellites, whereas a similar Eddington-limited active galactic nucleus (AGN) of 107 M⊙ has a temperature of 30–60 eV, in the unobservable EUV regime. Thus, stellar remnant black hole binary (BHB) systems give a much better test of disk models than AGNs.

The emission from each radius is a true blackbody only when the disk is effectively optically thick to absorption at all frequencies. Free-free (continuum) absorption drops as the frequency increases, so the highest energy photons from each radii are unlikely to thermalize. This forms instead a modified (or diluted) blackbody, with effective temperature higher than that for complete thermalization by a factor of $f_{\text{col}}$ (termed a color temperature correction). The full disk spectrum is then a sum of these modified blackbodies, but this can likewise be approximately described by a single color temperature correction to a sum of blackbody disk spectrum (Shimura & Takahara 1995). However, continuum processes do not necessarily dominate the total absorption at all frequencies. Bound-free (photoelectric) absorption from partially ionized metals can be important, especially at high frequencies where the free-free absorption becomes less significant (Davis et al. 2005). This imprints atomic features onto the emission from each radius, distorting the spectrum from a smooth continuum. The strength of these features is set by radiative transfer through the vertical structure of the photosphere, so they are one of the few diagnostics of the internal disk properties (Done & Davis 2008).

Thus, the intrinsic spectrum from each radius can be complex, but each of these is smeared out by the combination of special and general relativistic effects which arise from the rapid rotation of the emitting material in a strong gravitational field (Cunningham 1975). The resultant smeared spectra are summed together to form the total disk emission, which is not that different from a sum of smeared color temperature corrected blackbody spectra (Davis et al. 2005; Davis & Hubeny 2006; Done & Davis 2008). We need excellent data in order to detect these smeared spectral features, and use them to test our understanding of the disk vertical structure.

The BHB LMC X-3 is the best object currently known for this. It has the lowest absorption column density of any BHB which shows disk-dominated spectra, extending the bandpass over which the data can constrain the models down to the softest X-ray energies. Additionally, the system parameters are fairly well determined, especially distance which is known to better than 10% due to its location in the Large Magellanic Cloud. Thus, the conversion of flux to luminosity is subject to smaller uncertainties than for any other BHB. This combination

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of properties means LMC X-3 offers a unique laboratory for testing our understanding of accretion disk physics.

Here we use data from a Suzaku (Mitsuda et al. 2007) observation of the disk-dominated state in this object. This satellite combines moderate spectral resolution CCDs useful to constrain 0.7–10 keV spectrum of the source, together with the Si PIN photodiodes of the non-imaging Hard X-ray Detector (HXD; Takahashi et al. 2007) which can simultaneously determine the 12–30 keV spectrum. Thus, these data give a complete picture of the emission, being able to constrain the (weak) tail to higher energies which otherwise gives a significant source of uncertainty in reconstructing the disk spectrum from CDD data alone.

The spectrum of LMC X-3 during this observation is dominated by a clear disk component with luminosity around 10% of the Eddington limit. This is low enough to avoid the multiple uncertainties which arise at higher luminosities, where the disk may puff up due to radiation pressure, advection of radiation may become important, and strong winds from the inner disk can distort the spectrum both through absorption and from changing the intrinsic disk spectrum due to the mass loss. Thus, these observations give the most sensitive test to date of our understanding of a “clean” accretion disk to compare with the models.

2. OBSERVATION AND DATA REDUCTION

We observed LMC X-3 with Suzaku from 2008 December 22 UT 07:14 through December 23 UT 20:49 (epoch 5). Suzaku carries four X-ray telescopes (XRTs; Serlemitsos et al. 2007), each with a focal-plane X-ray CCD camera (X-ray Imaging Spectrometer, XIS; Koyama et al. 2007) operating in the energy range of 0.2–12 keV. Three of the XISs (XIS0, 2, and 3) have front-illuminated (FI) CCDs, while XIS1 utilizes a back-illuminated (BI) CCD, achieving an improved soft X-ray response but poorer hard X-ray sensitivity. Since XIS2 is no longer available, we use the two remaining FI-CCDs (XIS03) together with the BI-CCD (XIS1). We combine these with data from the Si PIN photodiodes of the HXD (Takahashi et al. 2007), which covers the 10–70 keV energy band.

The source was centered in the XIS field of view. The XISs were operated with the 1/4 window option so that pileup did not become significant. We use version 2.2.11.22 of the pipeline provided by the Suzaku team, and the XIS data are screened using the standard criteria (i.e., only GRADE0, 2, 3, 4, and 6 events are accumulated, time interval after passage through the South Atlantic Anomaly is longer than 436 s, the object is at least 5° and 20° above the Earth rim, time interval after passage through the South Atlantic Anomaly is longer than 436 s, the object is at least 5° and 20° above the Earth rim, day and night, respectively). This gives a net exposure of 73.98 ks.

We extract XIS events from both 5 × 5 and 3 × 3 edit modes using a circular region with a radius of 4.3 centered on the image peak. This is larger than the window size, so the effective extraction region is the intersection of the rectangular window with this circle. We use ftool xisrmfgen (version 2007-05-14) and xissimarfgen (version 2009-01-08) to calculate the response matrix and auxiliary response of the instrument. We co-add the data from the two FI CCDs as these are very similar, and generate the co-added response for this XIS03 spectrum using the ftools addrmf and addarf. We add systematic errors of 1% to each energy bin for both XIS03 and XIS1 spectra.

The source is bright, with count rate from XIS1 of 24 counts s⁻¹ in the range of 0.7–10 keV, which corresponds to 3.1 × 10⁻¹⁰ erg s⁻¹ cm⁻². Though background can be important toward the highest energy end of this bandpass, the large point-spread function of Suzaku means that the 1/4 window data cannot be used to simultaneously determine the background as there is no source-free region. Instead we use the Lockman hole data obtained by Suzaku from 2009 June 12 UT 07:17 through June 14 UT 01:31 with an exposure of a net exposure of 92 ks, using the same shaped (intersection of circle and rectangle) region. The background levels are negligible in soft energy band, and reach to ∼0.7% and ∼5% of our LMC X-3 data at 8 keV, for XIS03 and XIS1, respectively. In this paper, we used the 0.7–10 keV band and the 0.7–8 keV band for XIS03 and XIS1, respectively. We show the background-subtracted XIS03 and XIS1 spectra in Figure 1.

The HXD was operated in the nominal mode throughout the observations. We use the standard pipeline processed PIN data (object is at least 5° above the Earth rim, time interval after passage through the South Atlantic Anomaly is longer than 500 s, and cutoff rigidly is greater than 6 GV). We extract background from the same good-time intervals of the PIN background model based on LCFI/DT method (2.0VER0804) provided by the HXD team for each observation (Fukazawa et al. 2009). Here we note that the HXD-PIN background model is aimed to reproduce the non-X-ray background. The source exposure corrected for the 7.3% dead time, which is calculated from the pseudo event rates (Takahashi et al. 2007; Kokubun et al. 2007) by using the ftool hxddtcor, giving a net exposure of 70.03 ks. This is ∼25% less than the XIS, but the source shows little variability so we do not exclude any XIS data in order to have only exactly simultaneous data. These data show that the source is not significantly detected at the highest energies, so we restrict the fit range to 12–30 keV using the appropriate response ae_hxd_pinximome_3_20080716.rsp.

The background-subtracted PIN spectrum is shown in Figure 1 together with the XIS spectra. This has a 12–30 keV count rate of 0.076 counts s⁻¹. This corresponds to a flux of 2.2 × 10⁻¹¹ erg s⁻¹ cm⁻², which is only ∼4 times higher than the flux of the cosmic X-ray background (CXB) in the same energy range. Thus, the CXB is not negligible, and we include this as a fixed exponentially cutoff PL (Bolsh et al. 1987) in all our spectral modeling for the PIN data.8

Figure 1. Background-subtracted X-ray spectra of LMC X-3 obtained with XIS03 (black), XIS1 (red), and HXD PIN (green).

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

8 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pin_cxb.html
3. ANALYSES AND RESULTS

We describe here the system parameters of LMC X-3 adopted in this paper. LMC X-3 is a persistent source, so the emission from the outer accretion disk always contributes to the optical spectrum, and X-ray irradiation can alter the structure and spectrum of the companion star. This introduces some uncertainty in determining the properties of the companion, and hence the mass of the black hole (van der Klis et al. 1985; Cowley et al. 1983; Soria et al. 2001; Negueruela & Coe 2002). Taking account of the uncertainties, we consider the black hole mass in the range of 7–9 M⊙ and inclinations of 50°–67°. Thus, for each physical model (kerrbb and bhspec in xspec) we report fit values over this range, showing also results for the specific combination of 7 M⊙ and inclination of 67° used by Davis et al. (2006). We assume a source distance of 52 kpc (di Benedetto 1997).

We use the xspec spectral fitting package. Large fit residuals due to calibration uncertainties are often observed near the edge structures of the XIS/XRT instrumental responses. We exclude energy ranges of 1.6–2.0 keV and 2.2–2.4 keV, and model the remaining instrumental feature at ~3.2 keV by gold M edge by a Gaussian line with fixed Gaussian width of 0.1 keV as is done in Kubota et al. (2007).

The absorption column density is well determined as 3.8 × 10^20 cm^-2 (Page et al. 2003) from the depths of edges measured by the XMM-Newton Reflection Grating Spectrometer data. This is consistent with most of the absorption being due to our own Galaxy as the column density along this line of sight is 3.2×10^20 cm^-2 as measured by radio observations (Nowak et al. 2001). However, low-energy calibration (especially the quantum efficiency) of the Suzaku XIS suffers from relatively large systematic errors due to the uncertainties of the contamination thickness and its composition. To minimize the impact of these systematic errors while keeping good low-energy coverage, we restricted the energy range above 0.7 keV in the spectral analysis. In this energy range with the calibration database (caldb: version xis20090203), we estimate that the systematic error in determining N_H is about a few times 10^20 cm^-2 (XIS team 2009, private communication). Because this is comparable to the column density to LMC X-3, we allow N_H (described using phabs) to be free in the spectral analysis unless otherwise stated.

When we analyze the disk emission, it is important to model the power-law component appropriately, because its low-energy part sometimes affects the fitting of the disk emission. A simple power law (hereafter PL) plus CXB fit to the PIN data alone in the 12–30 keV band gives a photon spectral index of 1.66–2.38 with the best-fit value of 2.01. Because the power-law component in the high/soft state usually has a photon index larger than 2.0 (e.g., Done et al. 2007, and references therein), we consider that the true index of LMC X-3 lies between 2.00 and 2.38. Therefore, we constrain the index in this range in the spectral analysis rather than allowing it to be free. Otherwise, the power-law component would be optimized to fill the fit residuals in the low-energy band, where the statistics are much better than those of the HXD PIN, and the best-fit power-law index could significantly deviate from the true slope in the hard energy band.

3.1. Empirical Modeling of the Disk: diskbb

In order to compare the spectral data with the previous observations, we first use the common black hole spectral model of an absorbed disk plus power law. The simplest disk model is diskbb, which has a temperature distribution T(r) ∝ r^-3/4, i.e., has no stress-free inner boundary condition (Mitsuda et al. 1984; Makishima et al. 1986).

Figure 2 shows the XIS and the HXD/PIN spectra with this best-fit diskbb plus PL model, with parameters given in Table 1. The fit is well flat (χ^2/dof = 770.25/706) by the dominant diskbb component with T_in of 0.84 keV. The 0.7–30 keV flux is estimated as 3.30 × 10^-10 erg s^-1 cm^-2, which gives an absorbed X-ray luminosity as 1.07 × 10^38 erg s^-1 for an isotropic emission at D = 52 kpc. This luminosity is about 10% of the Eddington luminosity for a 7 M⊙ black hole, and is the same level as that seen in the dimmer of the two ASCA observations reported by Kubota et al. (2005). The radius derived from the diskbb normalization, r^2_o / (D/10 kpc)$^2 = 26.0±0.3$, is also consistent with the values of 25 ±3 and 24 ±2 obtained from the ASCA observations (Kubota et al. 2005).

Even though the fit is good, a closer inspection of the figure shows that this is not a good physical description of a model where the disk provides the seed photons for Compton upscattering into the power-law tail as the PL extends below the disk at low energies. Hence we replace the PL model with the simpl. (Steiner et al. 2009) model for Compton upscattering. This takes some fraction of the disk seed photons and upscatters these to higher energies. It is a convolution model, so requires an extended energy range which we fix at 0.1–1000 keV.

The fit becomes substantially worse with this more physical model (χ^2/dof = 1336/706), as shown by the residuals between the data and the best-fit simpl*diskbb model (Figure 2(c)). In addition, N_H is much smaller than expected, even though it is comparable to the current systematic uncertainty of the N_H determination with the XIS. Both these effects show that the observed disk shape gives the excess at lower energies. In other words, a peak profile of the observed disk spectrum corresponding to the maximum disk temperature is much broader than predicted by diskbb, motivating us to do more detailed spectral analyses. Similar conclusions were reached by...
Davis et al. (2006), who analyzed BeppoSAX data. Although their data had poorer signal-to-noise ratio, it had similar low energy coverage and they also found poor fits with DISKBB once the PL was reasonably constrained.

3.2. Effect of the General Relativity: Temperature Profile and Relativistic Smearing: DISKPN and KERRBB

We now use progressively more complex models for the disk emission together with the SIMPL Compton upscattering model for the tail. First, we consider the DISKPN model which includes the stress-free inner boundary condition assuming a Paczynski–Wiita (pseudo-Newtonian) potential. This smoothly connects the temperature profile from $T(r) \propto r^{-3/4}$ at large radii, and $T(r_{in}) = 0$ at $r_{in}$, where $r_{in} = 6R_g$, in a way which is similar to that expected from the fully relativistic equations for a zero-spin black hole (Gierliński et al. 1999). This has the effect of broadening the spectrum slightly as it reduces the emission from the hottest material, and hence gives a better fit to the data ($\chi^2_\nu = 984/706$) than the SIMPL*DISKBB, though still not as good as the unphysical DISKBB+PL model. This indicates that the soft component in the data is still broader than the DISKPN description. Relativistic corrections to the temperature profile alone do not sufficiently broaden the spectrum to match the observed data.

The next step up in complexity is to include the special and general relativistic effects which distort the observed spectrum at each radius. We use the KERRBB model (Li et al. 2005) for this, which calculates the intrinsic temperature distribution from a fully relativistic, stress-free inner boundary condition for arbitrary spin, multiplied by a color temperature correction factor, $f_{col}$, to approximate the effect of modified blackbody emission. We fixed $f_{col} = 1.7$ as appropriate for the XIS CCD bandpass at this luminosity (Done & Davis 2008). This intrinsic emission from each radius is convolved with the relativistic transfer function for that radius and assumed disk inclination (Li et al. 2005).

We explore the dependence on mass and inclination by fitting the model with different combinations of these two parameters. These fit results are shown in Table 2 and Figure 3. These all give a fit which is similarly good as that derived from the DISKBB+PL model (see Table 2). The quality of the fit is not very dependent on mass and inclination, but the derived value of the spin changes from almost zero (lowest black hole mass, highest inclination) to $\sim 0.7$ (highest black hole mass and lowest inclination).

We illustrate the fit in Figure 3(a), showing the $\nu F_\nu$ spectrum and residuals for the models with mass of 7 $M_\odot$ and inclination of 67°, as used by Davis et al. (2006). This gives a good fit ($\chi^2_\nu = 776/706$) with flat residuals across the whole energy band (see Figure 3(b)), and gives a spin of $a^* \simeq 0$, consistent with that derived by Davis et al. (2006). Relativistic effects on the disk continuum were first proposed by Cunningham (1975), but this is the first time they have been significantly detected, as it is much harder to disentangle this smearing on a broad continuum than on a line (Fabian et al. 1989). Though the smaller values of $N_H$ may suggest that the data still have excess soft emission and are somewhat broader even than that produced by the temperature profile and relativistic broadening, the calibration uncertainties do not enable us to conclude unambiguously whether there are other broadening factors.

3.3. Effect of the Vertical Structure of the Disk: BHSPEC

The assumption of a constant $f_{col}$ is only an approximation to the true spectrum from a given radius. In the real disk, changes in opacity at atomic edges produce spectra intrinsically broader than a blackbody. Under the assumption of the solar metallicity, the BHSPEC model (Davis et al. 2005) uses radiative transfer to calculate the intrinsic spectrum at a given radius, so does self-consistently includes the color temperature correction. It then convolves this with the relativistic transfer functions to produce the best disk spectra to date.

We fit the spectra with the BHSPEC disk model for the same combinations of $i$ and $M$ as for the KERRBB fits above. The results are shown in Table 3. The model gives similar spins to those derived from KERRBB (see Table 2), showing that the assumption of $f_{col} = 1.7$ is appropriate to the KERRBB fit for the XIS CCD bandpass. Moreover, the estimated absorption is now consistent with the known column density in this direction $\sim 3 \times 10^{20}$ cm$^{-2}$. Thus, the BHSPEC model produces additional
excess soft emission than produced by relativistic broadening alone. However, despite being a more physical model, it gives much worse fits than \textsc{kerrbb} ($\chi^2$/dof = 1212/706 for the case of $M = 7 M_\odot$ and $i = 67^\circ$ compared to 784/706). Figure 4 shows the residuals between the data and the model for each mass and inclination. These are all clearly dominated by a broad feature below 1 keV, which is caused by the smeared atomic absorption edges present in the model.

We checked the result by including relativistically smeared ionized reflection, modeled using the convolution version of the models of Ballantyne et al. (2001) as described in Done & Gierliński (2006). Though the reflection itself cannot be well constrained because of couplings to mass, inclination, and the difference of the continuum disk model, it does not change this conclusion: \textsc{bhspec} gave a worse fit to the data than \textsc{kerrbb} if we did not constrain its absorption, and the \textsc{bhspec} residuals are dominated by features around 1 keV.

3.4. Constraint on the Absorption Lines Due to Highly Ionized Iron

Absorption lines from highly ionized hydrogen (H-) and helium (He-) like iron are often seen in disk-dominated BHBs (see, e.g., the compilation in Done et al. 2007). We focus on the iron K line region to sensitively search for such features. We fit the 5–8 keV data with a power law and narrow absorption line (with width fixed at 10 eV). There is evidence for such a line at 6.61 ± 0.04 keV, of equivalent width of −15 ± 6 eV.

Though this is significant at about the 99% confidence level on an $F$-test as $\chi^2$ drops from 233/221 to 215/219, the line energy is slightly too low to be He-like iron at 6.70 keV, even if we consider the calibration uncertainty of the gain, ~20 eV, when the 1/4 window option is used.\textsuperscript{10} The difference may be even larger, because the lines are often blueshifted due to the disk wind. As seen in the \textit{Chandra}/HETGS spectra of GX 13+1 (Ueda et al. 2004) and GRS 1915+105 (Ueda et al. 2009), He-like iron energy can be observed at lower energies than the prediction. Ueda et al. (2009) suggested that the slight shift of the line energy can be caused by a possible contamination of less ionized ions such as Li-like ones at 6.68 keV, uncertainties in the incident line energies for He-like (and more electrons) iron, and/or the velocity-field structure in the wind along the line of sight. However, even considering these effects and the XIS calibration uncertainty, 6.61 ± 0.04 keV is still difficult to be interpreted as He-like iron absorption lines. Fixing the line energy at 6.70 keV gives $\chi^2$ = 226/220, so again formally significant at the ~99% level, with an equivalent width of −9 ± 6 eV. This value represents the conservative constraint on the He-like iron absorption line.

Other BHBs at similar continuum luminosities ($\sim 10^{38}$ erg s$^{-1}$) show absorption lines of equivalent width of ~30 eV in both H- and He-like iron (e.g., GRO J1655–40, Ueda et al. 1998; Yamaoka et al. 2001; Miller et al. 2006a; 1H 1743–322, Miller et al. 2006b). These BHBs all have similar inclination angles of $i \sim 70^\circ$. Thus, less significant absorption lines may indicate that the inclination is likely to be lower than $67^\circ$. Alternatively, these BHBs showed higher disk temperature $T_{\text{in}}$ than our LMC X-3 data, typically at $\gtrsim 1.0$ keV when they showed absorption lines, and thus the disk temperature may also be important in creating the disk wind in addition to the luminosity.

4. DISCUSSION AND CONCLUSIONS

4.1. Black Hole Spin

The resulting values of spin are fairly similar for both \textsc{bhspec} and \textsc{kerrbb} with $f_{\text{col}} = 1.7$, giving a range in spin from 0 to 0.7 depending on mass and inclination. Although this seems a large range, it only corresponds to a change in inner radius by less than a factor of 2, from $6R_g$ at $a^* = 0$ to $3.4R_g$ at $a^* = 0.7$, whereas for extreme spin at $a^* = 0.998$ the inner radius becomes as small as $1.23R_g$. Thus, the models are not very sensitive to spin for low-to-moderate spin, even for the best-constrained black hole system parameters, as the implied change in radius for the

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Table 2: The Best-fit Parameters Based on the \textsc{kerrbb} Model

| Mass ($M_\odot$) | $i$ (deg) | $N_H$ ($10^{20}$ cm$^{-2}$) | $\alpha^*$ | $M^b$ ($10^{18}$ g s$^{-1}$) | $\Gamma$ | $f$ | $\chi^2$/dof |
|-----------------|----------|-----------------|----------|-----------------|---------|--|----------------|
| 7               | 67       | 0.16 ± 0.14     | −0.07 ± 0.01 | 3.32 ± 0.03      | 2.38$^{+0.04}_{-0.02}$ | 0.093$^{+0.002}_{-0.004}$ | 783.58/706 |
| 7               | 50       | 0.8 ± 0.1       | 0.53$^{+0.010}_{-0.007}$ | 1.27 ± 0.01      | 2.37$^{+0.01}_{-0.10}$ | 0.088$^{+0.003}_{-0.008}$ | 772.86/706 |
| 9               | 67       | 0.3 ± 0.1       | 0.29$^{+0.003}_{-0.009}$ | 2.58 ± 0.02      | 2.38$^{+0.01}_{-0.06}$ | 0.091$^{+0.002}_{-0.005}$ | 776.33/706 |
| 9               | 50       | 1.0 ± 0.2       | 0.738 ± 0.007 | 1.005 ± 0.009    | 2.31$^{+0.07}_{-0.09}$ | 0.082$^{+0.008}_{-0.007}$ | 776.70/706 |

Notes. Same as Table 1 but for the \textsc{kerrbb} model.

\textsuperscript{a} Black hole spin parameter.

\textsuperscript{b} Mass accretion rate of the \textsc{kerrbb} model.

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Figure 4. Residuals between the data and the best-fit \textsc{bhspec} models with different mass and inclination. (a) $M = 7 M_\odot$ and $i = 67^\circ$, (b) $M = 7 M_\odot$ and $i = 50^\circ$, (c) $M = 9 M_\odot$ and $i = 67^\circ$, and (d) $M = 9 M_\odot$ and $i = 50^\circ$. (A color version of this figure is available in the online journal.)
last stable orbit is low. However, they are very sensitive to high spin, and strongly rule out such values for LMC X-3.

Hence we conclude that the black hole in LMC X-3 has low-to-moderate spin. This is also the case for all other spin determinations from disk-continuum fits (Davis et al. 2006; Shafee et al. 2006; Gou et al. 2009), apart perhaps from GRS 1915+105 (McClintock et al. 2006, but see Middleton et al. 2006). Such low-to-moderate spins are in line with current (but probably quite uncertain) theoretical models which indicate birth spins of $\lesssim 0.8$–0.9 from stellar collapse (Gammie et al. 2004). However, we note that the iron line fits often imply rather higher spins, sometimes for the same objects (e.g., Miller et al. 2009). This is clearly an area of current intense research (see, e.g., the discussion in Kolehmainen & Done 2009).

4.2. Vertical Structure

The Suzaku observation of LMC X-3 shows a spectrum which is dominated by the accretion disk, giving the best data yet on its detailed spectrum, and a simultaneous determination of the high-energy tail. We model the tail as Compton upscattering of seed photons from the disk. The disk spectrum is much broader than a simple sum of blackbodies with $T(r) \propto r^{-3/4}$ (diskbb). It is also broader than a sum of blackbodies with temperature profile given by the (approximate) stress-free inner boundary condition in the pseudo-Newtonian potential (diskpkn). Relativistic smearing of the intrinsic blackbody spectra from each radius (with temperature profile given by the stress-free inner boundary condition) is required before the model gives a good description of the overall shape of the data (kerrbb), though the kerrbb model also requires an absorption column close to zero.

The bhspec model dispenses with the color temperature correction by calculating the spectrum self-consistently from radiative transfer through the vertical structure of the disk. The column density derived from this model is consistent with the known column, but the fit is poor due to residuals at 1 keV. In order to clarify the reason for the residuals seen in the bhspec fit, Figure 5 shows a comparison of the best-fit bhspec model with that of kerrbb. The bhspec model gives more soft emission below 1 keV, and it does this due to the presence of absorption edges, most importantly the K edges of H-like nitrogen and oxygen at 0.66 keV and 0.87 keV, respectively. Though these are broadened and smeared by the relativistic effects, they are still deeper than any features present in the data, so appear in the residuals as an excess at the absorption edge energy. These residuals are around 5% (peak-to-peak), but the data are actually consistent with no structure at these energies, as seen by the featureless residuals from the best-fit kerrbb model (Figure 3(b)).

To reduce the size of the atomic features, we first consider sub-solar abundances, since the LMC is suggested to have 1/2–1/3 solar abundance (Russell & Bessell 1989; Russell & Dopita 1990; Korn et al. 2002). In order to examine this effect, we

| Mass ($M_\odot$) | $i$ (deg) | $N_H$ ($10^{20}$ cm$^{-2}$) | $a^*$ | $L_{\text{disk}}$ ($10^{38}$ erg s$^{-1}$) | $\Gamma$ | $f$ | $\chi^2$/dof |
|----------------|-----------|--------------------------|--------|-----------------|-------|-----|----------------|
| The solar abundance | | | | | | |
| 7 | 67 | 2.7 ± 0.1 | $-0.082^{+0.022}_{-0.008}$ | 1.799 ± 0.005 | 2.380$^{+0.000}_{-0.006}$ | 0.102$^{+0.003}_{-0.002}$ | 1212.47/706 |
| 7 | 50 | 3.9 ± 0.1 | 0.542 ± 0.006 | 1.054$^{+0.002}_{-0.003}$ | 2.380$^{+0.008}_{-0.008}$ | 0.096 ± 0.002 | 1058.56/706 |
| 9 | 67 | 3.1 ± 0.1 | 0.286 ± 0.009 | 1.748 ± 0.005 | 2.380$^{+0.000}_{-0.006}$ | 0.100 ± 0.001 | 1094.30/706 |
| 9 | 50 | 4.3 ± 0.1 | 0.742 ± 0.004 | 1.085$^{+0.002}_{-0.003}$ | 2.380$^{+0.010}_{-0.010}$ | 0.094 ± 0.002 | 974.65/706 |
| 1/3 solar abundance | | | | | | |
| 7 | 67 | 1.6 ± 0.1 | $-0.076 ± 0.010$ | 1.765$^{+0.005}_{-0.004}$ | 2.380$^{+0.007}_{-0.007}$ | 0.102 ± 0.002 | 1151.91/706 |
| 7 | 50 | 2.7 ± 0.1 | 0.536 ± 0.006 | 1.033 ± 0.002 | 2.380$^{+0.008}_{-0.008}$ | 0.098 ± 0.002 | 1062.58/706 |
| 9 | 67 | 2.0 ± 0.1 | 0.278 ± 0.009 | 1.717 ± 0.005 | 2.380$^{+0.006}_{-0.006}$ | 0.102 ± 0.002 | 1063.26/706 |
| 9 | 50 | 3.1 ± 0.1 | 0.737 ± 0.004 | 1.061 ± 0.002 | 2.380$^{+0.009}_{-0.009}$ | 0.096 ± 0.002 | 987.75/706 |
| 1/10 solar abundance (just for comparison) | | | | | | |
| 7 | 67 | 0.7 ± 0.1 | $-0.049 ± 0.010$ | 1.725$^{+0.005}_{-0.004}$ | 2.380$^{+0.008}_{-0.008}$ | 0.102 ± 0.002 | 1014.46/706 |
| 7 | 50 | 1.69 ± 0.1 | $0.558^{+0.007}_{-0.006}$ | 1.011$^{+0.002}_{-0.003}$ | 2.380$^{+0.008}_{-0.008}$ | 0.099 ± 0.002 | 974.17/706 |
| 9 | 67 | 1.0$^{+0.2}_{-0.1}$ | $0.304^{+0.009}_{-0.010}$ | 1.680 ± 0.005 | 2.380$^{+0.009}_{-0.009}$ | 0.101 ± 0.002 | 973.39/706 |
| 9 | 50 | 2.0 ± 0.1 | 0.748 ± 0.004 | 1.039$^{+0.002}_{-0.003}$ | 2.380$^{+0.010}_{-0.010}$ | 0.097 ± 0.002 | 919.16/706 |

Note. Same as Tables 1 and 2 but for the bhspec model.
extended the original BHSPEC model to account for sub-solar metallicity. We fit the data with the new BHSPEC disk model of fixed 1/3 solar metallicity for the same combinations of $i$ and $M$ as used previously. The results and fit residuals are shown in Table 3 and Figure 6, respectively. For the condition of $M = 7\,M_\odot$ and $i = 67^\circ$, the best-fit BHSPEC model with 1/3 solar abundance is shown in Figure 5 together with the original BHSPEC and KERRBB models. The lower abundance means that the absorption edge structure below 1 keV is less significant ($\chi^2 / \nu = 1152/706$ for $M = 7\,M_\odot$ and $i = 67^\circ$), though the residuals are still clearly dominated by the edge structure below 1 keV. We also show the fit results based on the BHSPEC with 1/10 solar abundance in Table 3, Figure 7, and Figure 5. Even though this is an underestimate of the metallicity, the predicted edge features are still larger than those seen in the data (Figure 7), and thus the fits are worse than the KERRBB.

This illustrates the key issue. Using the CALDB version XIS20090203, the data indicate that the spectrum is broader than a single color temperature corrected, relativistically smeared model (KERRBB). Including ion opacities as in BHSPEC gives broader spectra, but with the inevitable consequence edge features are predicted. Since there is no evidence for these edges in the spectrum, incorporating sub-solar abundances alone in BHSPEC cannot explain why the model does not reproduce the data.

Instead, this could point to the importance of including more atomic physics in BHSPEC. Currently it only uses bound–free opacity, but bound–bound (line) transitions could also be important, especially if there is large-scale turbulence/convective motion in the disk atmosphere. However, if these additional transitions primarily show up as absorption features, they will further enhance the depth of the atomic absorption, increasing the discrepancies. Instead, line and/or radiative recombination continuum emission could fill in some of the absorption features, while still retaining the broader continuum, though this seems somewhat fine-tuned. Self-irradiation of the disk may be a better mechanism, as this would drive the photosphere toward isothermality, removing the atomic features which do not appear to be present in the data but keeping the broader continuum.

Whatever the origin of the fit residuals, their existence demonstrates the possibility of using the observational data to discriminate between different models of the vertical structure of the accretion disk, and motivates the development of more sophisticated disk atmosphere calculations.

We are grateful to all the Suzaku team members. We also thank the anonymous referee for his/her helpful comments. The present work is supported by grant-in-aid 19740113 from Ministry of Education, Culture, Sports, Science and Technology of Japan. S.W.D. acknowledges support from the IAS, through grants NSF AST-0807432, NASA NNX08AH24G, and NSF AST-0807444.

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