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SPECTRAL VARIATIONS OF LMC X-3 OBSERVED WITH *GINGA*

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ABSTRACT

The prime black hole candidate LMC X-3 was observed over 3 yr with the *Ginga* satellite, and a characteristic spectral variation was found accompanying the periodic intensity variation of ~198 (or possibly ~99) days (Cowley et al. 1991). The energy spectrum of LMC X-3 consists of the soft, thermal component and the hard, power-law component, which are respectively dominant below and above ~9 keV. The soft component, which carries most of the X-ray intensity, shows a clear correlation between the intensity and the hardness, while the hard component varies independently of the soft component. It was found that the spectral variation of the soft component is well described by an optically thick accretion disk model with a remarkably constant innermost radius and variable mass accretion rate. The constancy of the innermost radius suggests it is related to the mass of the central object. Supposing that the innermost radius of the accretion disk is the last stable orbit around a black hole, i.e., 3 times the Schwarzschild radius, we estimate the mass of the central object in LMC X-3. Satisfactory agreement has been found between the mass thus derived and the fiducial mass lower limit determined from observations of the binary motion.

Subject headings: X-rays: stars

1. INTRODUCTION AND SUMMARY

LMC X-3 is considered a firm black hole candidate owing to the much larger mass of the compact object ($M \gtrsim 7\ M_\odot$; Cowley et al. 1983; Paczyński 1983) than the currently accepted maximum neutron star mass ($\sim 3\ M_\odot$; Rhoades & Ruffini 1974; Arnett & Bowers 1977; Hartle 1978). The X-ray energy spectrum of LMC X-3, as well as those of other black hole candidates, is known to be characterized by its "ultra-softness" compared to the spectra of binary X-ray sources containing neutron stars (White & Marshall 1984; White, Kaluzianski, & Swank 1984).

The *Ginga* satellite observed LMC X-3 intermittently over 3 yr. The intensity of LMC X-3 varied by a factor of ~4 with a periodicity of ~198 days (or possibly ~99 days; Cowley et al. 1991, hereafter Paper I). In the course of the observations, a clear correlation was found between the X-ray intensity and hardness below ~9 keV, but the intensity above ~9 keV did not show such a clear correlation (Paper I). From one of these *Ginga* observations, it was found that the energy spectrum of LMC X-3 comprises the (ultra-)soft component and an additional hard-tail component which is conspicuous above ~9 keV (Treves et al. 1990).

In this paper, we present results of a detailed study of the energy spectrum of LMC X-3 over the significant intensity and spectral variations. In the context of the two-component model, it was found that hardness (or temperature) of the soft component clearly correlates with its intensity, but the hard component varies independently from the soft component.

The most important result is that the spectral variation of the soft component can be described by an optically thick accretion disk model with a remarkably constant innermost radius and variable mass accretion rate. Considering the constant innermost radius of the accretion disk to be the last stable orbit around a black hole, i.e., 3 times the Schwarzschild radius, we estimate the mass of the central object in LMC X-3. The mass thus derived shows satisfactory agreement with the fiducial lower limit of the mass derived from observations of the binary motion. The present result strongly suggest that the soft component of LMC X-3 is emission from an optically thick accretion disk, and the innermost radius of the accretion disk is directly related to the mass of the central object.

2. OBSERVATIONS AND RESULTS

2.1. *Observations*

Observations were made with the Large Area Counters (LAC) on board the *Ginga* satellite (Turner et al. 1989) from 1987 March to 1990 March. The energy range of the LAC is 1.2–37 keV with 48 energy channels for the MPC1 and MPC2 modes. The data are classified into four categories according to the method of acquisition: (i) those taken by dedicated pointing, (ii) slow scanning observations, (iii) those taken by chance during slow maneuvering, and (iv) quick slewing of the satellite (see Paper I). In the present paper, data taken during quick slewing are not used since the statistics are too poor for spectral analysis. The log of the observations, the intensity, and the hardness of all the data are found in Table 1 of Paper I.

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Here, we would like to correct a few errors in Table 1 of Paper I, which were found after publication and are due to a bug in a *Ginga* data analysis program which determined the intensity of the source from scan data. For the MPC2 data, the program counted only four of the eight counters and ignored the other half. Accordingly, these intensities from scan data were incorrect. After correcting the program and reanalyzing the data, we obtained intensities for the MPC2 scan data on two dates: on $JD_{Mid} = 2{,}400{,}000 + 7227.744$, the intensity in 1.2–18.6 keV is 250 ± 21 LAC counts s^{-1}, and on $JD_{Mid} = 2{,}400{,}000 + 7742.288$ (these data are annotated MPC1 in Table 1 of Paper I, but this should be read as MPC2), it is 191 ± 8 LAC counts s^{-1} (errors are for the 90% confidence limit). Resultant changes of the hardnesses are insignificant within the errors. Since the MPC2 data were not used for the period analyses in Paper I, the results are unchanged.

2.2. *Spectral Variations*

Figures 1*a* and 1*b* shows the hardness ratio (4.7–9.3 keV)/(1.2–4.7 keV) (soft-hardness) against the intensity in 1.2–9.3 keV and the hardness ratio (9.3–18.6 keV)/(4.7–9.3 keV) (hard-hardness) against the intensity in 1.2–18.6 keV. As was pointed out in Paper I, a positive correlation of the soft-hardness with the intensity is evident, but such a clear correlation was not found between the hard-hardness and the itensity. A similar intensity-hardness correlation of LMC X-3 in $\lesssim 10$ keV was also noted in *Einstein* MPC observations (Weisskopf et al. 1983) and *HEAO 1* observations (Cowley et al. 1991).

The energy spectrum of LMC X-3 comprises the soft, thermal component and the hard, power-law component; they are respectively dominant below and above ~9 keV (Treves et al. 1990). In terms of the two spectral components, the spectral variation in Figure 1 suggests that the soft component hardens as the intensity increases, but the hard component varies independently of the soft component.

Treves et al. (1990) have shown that the soft component of LMC X-3 can be fitted with the multicolor disk model (Mitsuda et al. 1984; Makishima et al. 1986), which approximates emission from optically thick accretion disks, or with the Comptonized spectrum by Sunyaev & Titarchuk (1980) (see also Treves et al. 1988b; White, Stella, & Parmar 1988). In the multicolor disk model, a local temperature of the disk varies as $T \propto r^{-3/4}$, so the spectrum is determined only by the innermost radius and the temperature. In Figures 1*a* and 1*b*, we show a trace of the multicolor disk model with a constant innermost radius $[r_{in}(\cos\theta)^{1/2} = 25.5$ km at a distance of 55 kpc, where θ is the inclination angle of the disk] and a variable innermost temperature from $T_{in} \sim 0.9$ keV to ~ 1.3 keV. In Figure 1*a*, it can be clearly seen that the intensity-hardness relation of the soft component is successfully described by this model. In an optically thick accretion disk with a constant emission area, the temperature of the disk increases with the mass accretion rate. Therefore, in terms of an optically thick accretion disk model, the spectral variation of the soft component can be simply ascribed to the variations of the mass accretion rate.

2.3. *Spectral Fitting*

In Figure 1*b*, upward excursions of the data from the model curve may be ascribed to erratic variations of the hard component. The four data points marked with arrows are consistent with the model curve, within ~ the 2 σ level, and are considered to have very weak or no hard components. Therefore, these four data points seem to be most suitable to investigate the spectral shape of the soft component without contamination of the hard component.

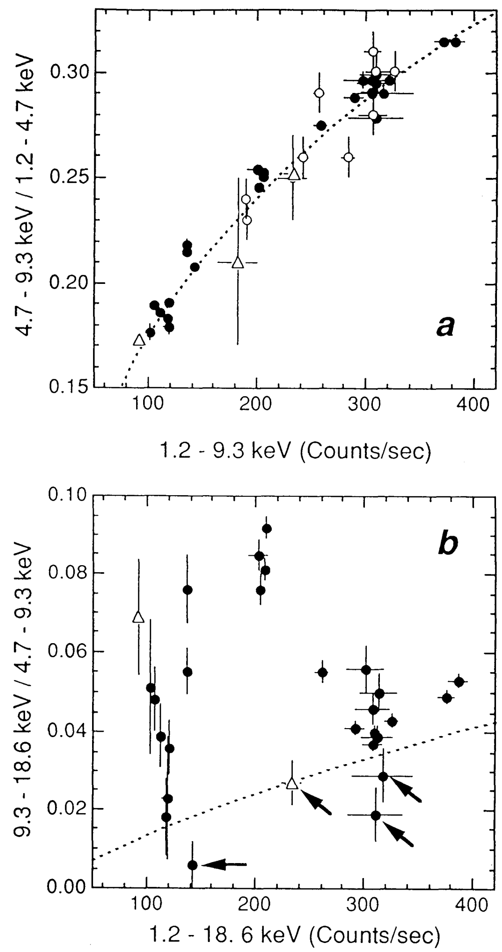

FIG. 1.—The intensity-hardness diagram of LMC X-3. (*a*) intensity in 1.2–9.3 keV vs. hardness in (4.7–9.3 keV)/(1.2–4.7 keV); (*b*) intensity in 1.2–18.6 keV vs. hardness in (9.3–18.6 keV)/(4.7–9.3 keV). Filled circles, open circles, and triangles respectively denote the data taken by pointing, scanning, and during maneuver of the satellite. In (*b*), those data with insufficient statistics (scanning data and maneuvering data with short exposure) are not shown. The dotted line indicates a trace of the multicolor disk model with a fixed innermost radius $[r_{in}(\cos\theta)^{1/2} = 25.5$ km at a distance of 55 kpc] and variable temperatures ($T_{in} \sim 0.9$ keV to ~ 1.3 keV). From (*a*), it can be clearly seen that the spectral variation of the soft component is well described by this model. Upward excursions of the data points in (*b*) from the model curve may be ascribed to erratic variations of the hard component. The data points marked with arrows in (*b*) are considered to have negligibly small hard component since they are consistent with the model curve within the 2 σ level.

Results in the previous subsection strongly suggest that the soft component can be represented with an optically thick accretion disk model. The multicolor disk model, however, is too simple to obtain physical parameters of the optically thick accretion disk through model fitting. In the inner region of an optically thick accretion disk, where most X-ray photons are emitted, the emission is not a true blackbody, because electron scattering dominates the opacity and modifies the spectrum (Shakura & Sunyaev 1973). In such a case, the color temperature of the emission becomes higher than the effective temperature (Ebisuzaki, Hanawa, & Sugimoto 1984; London, Taam, & Howard 1986). Furthermore, the simple relation assumed in the multicolor disk model, $T \propto r^{-3/4}$, does not hold near the inner edge of the disk because of the inner boundary condition (Shakura & Sunyaev 1973). Relativistic effects due to fast disk rotation and strong gravity might modify the disk emission near the black hole too. These effects should be taken into account in order to obtain physical parameters of the accretion disk from model fitting.

To that end, we adopted general relativistic accretion disk model (hereafter GRAD model) calculated by Hanawa (1989) (see also Ebisawa, Mitsuda and Hanawa 1991; Ebisawa 1991). In the GRAD model, it is assumed that (i) the accretion disk is rotating in the Schwarzschild spacetime, (ii) the radius of the inner edge of the disk is the innermost stable Keplerian orbit around a black hole, i.e., 3 times the Schwarzschild radius, and (iii) a local part of the disk has a blackbody-like spectrum, $I_\nu = (T_{\rm eff}/T_{\rm col})^4 B_\nu(T_{\rm col})$. Given the distance to the source, the GRAD model has four parameters; the mass of the central object, M; the mass accretion rate, $\dot{M}$; the inclination angle of the disk, i; and the ratio of the color to the effective temperature of the emission, $T_{\rm col}/T_{\rm eff}$. It has been shown that the spectral shapes of the multicolor disk model and the GRAD model are very similar to each other when the inclination angle is $\sim 0°$ (a face-on disk), but the difference becomes noticeable due to relativistic effects as the inclination angle increases (although the difference is at most $\sim 3\%$ when $i \sim 60°$; Ebisawa et al. 1991; Ebisawa 1991).

We applied the GRAD model to the four spectra with negligible hard components (Table 1). Throughout the fitting procedure, the distance to the source is taken as 55 kpc and the value of $T_{\rm col}/T_{\rm eff}$ is fixed at 1.5. The latter value is adopted from calculations of bursting neutron star atmospheres in which electron scattering opacity is also dominant (Ebisuzaki et al. 1984; London et al. 1986). It is difficult to make the inclination angle free in the fits because of the strong interdependence between the parameters. Therefore, the fitting was made with fixed inclination angles; we have chosen conventionally $i = 0°$ and 60°. Thereby the free parameters of the fitting are M, $\dot{M}$, and the column density of the interstellar hydrogen, $N_{\rm H}$.

Results of the spectral fitting with the GRAD model are shown in Table 1 (for $i = 0°$) and Table 2 (for $i = 60°$). Corresponding to the fact that the inner radius of the multicolor disk model is nearly constant (Fig. 1*a*), the mass of the GRAD model is virtually invariable through the four spectra. It is also found that the GRAD model with $i = 60°$ gives a better fit than that with $i = 0°$ for three of the four spectra. This is consistent with the findings of Treves et al. (1988a) and Kuiper, van Paradijs, & van der Klis (1988), who on the basis of optical and UV photometry suggest a value of the inclination close to 60°.

We also fitted these four spectra with the Comptonization model of Sunyaev & Titarchuk (1980) (Table 3). This model, first proposed for LMC X-3 by Treves et al. (1988b) and White et al. (1988), has three free parameters: normalization N (which is directly related to the number of input soft photons), electron temperature of the hot plasma T_e, and the electron scattering optical depth of the plasma τ_e. The Comptonization model can also fit all the spectra satisfactorily (Table 3). However, the spectral variation is realized by a complicated correlation among the three parameters, and such an invariant as the mass of the central object in the GRAD model cannot be found with the Comptonization model.

Solely from the spectral fitting, it is impossible to choose between the GRAD model or the Comptonization model since both of them yield satisfactory fits (in fact, the spectral shapes are very similar to each other; see Ebisawa et al. 1991). However, we consider it significant that the observed spectral variation can be naturally understood with the GRAD model as constancy of the mass of the central object and variation of the mass accretion rate, but not with the Comptonization model. This strongly suggests that the soft component of LMC X-3 is emission from an optically thick accretion disk, and the innermost radius of the disk is directly related to the mass of the central object.

We next applied the GRAD model of $i = 60°$ to the spectrum whose hard component is the strongest (1988 January). An acceptable fit was obtained with an additional power-law function for the hard component (Table 4). In Figure 2, results of the spectral fitting are shown for two contrasting spectra, one of which has no hard component (1988 March) and the other has the strongest hard component (1988 January).

For the other spectra, the hard components are not negligible, but not enough strong for the photon indices to be uniquely determined. Therefore, the spectral fit was made with the GRAD model of $i = 60°$ plus a power-law function with a fixed photon index at the best-fit value for the 1988 January spectrum, 2.21. We obtained acceptable fits at the 90% significance level for 12 of the 14 spectra with this model (Table 5).

Time variation of the parameters from the spectral fitting (M, $\dot{M}$, the luminosity of the hard component) are shown in Figure 3. It is obvious that M is remarkably constant throughout the observations. The hard component is largely variable without a clear correlation to the soft component. It was

TABLE 1

SPECTRAL FITTING WITH THE GRAD MODEL ($i = 0°$)[a,b]

Parameter	1987 Apr	1988 Mar	1989 Oct	1989 Dec 19
M ($M_\odot$)	2.75 ± 0.06	2.65 ± 0.04	2.52 ± 0.06	2.67 ± 0.06
$\dot{M}$ (10^{18} g s^{-1}) ...	4.76 ± 0.05	3.75 ± 0.04	2.52 ± 0.05	4.86 ± 0.05
log $N_{\rm H}$ (cm^{-2}) ...	<20.7	<20	$20.8 \pm ^{0.3}_{0.6}$	<20.7
Reduced χ^{2}[c]	2.01	2.83	2.00	1.19

[a] Quoted uncertainties are single-parameter 90% confidence limit.
[b] Distance to the source is assumed to be 55 kpc.
[c] For 18 degrees of freedom.

TABLE 2

SPECTRAL FITTING WITH THE GRAD MODEL ($i = 60°$)[a,b]

Parameter	1987 Apr	1988 Mar	1989 Oct	1989 Dec 19
M ($M_\odot$)	5.45 ± 0.20	5.12 ± 0.10	5.40 ± 0.13	5.39 ± 0.22
$\dot{M}$ (10^{18} g s^{-1}) ...	7.95 ± 0.17	6.13 ± 0.06	4.41 ± 0.10	8.20 ± 0.19
log $N_{\rm H}$ (cm^{-2}) ...	21.0 ± 0.3	<20.5	21.4 ± 0.1	21.1 ± 0.3
Reduced X^{2}[c]	1.45	1.01	0.35	1.30

[a] Quoted uncertainies are single-parameter 90% confidence limit.
[b] Distance to the source is assumed to be 55 kpc.
[c] For 18 degrees of freedom.

TABLE 3

SPECTRAL FITTING WITH THE COMPTONIZATION MODEL[a]

Parameter	1987 Apr	1988 Mar	1989 Oct	1989 Dec 19
Scale[b]	12.1 ± 1.7	11.0 ± 1.4	6.8 ± 0.8	15.5 ± 2.9
T_e (keV)	1.15 ± 0.03	1.10 ± 0.03	1.04 ± 0.02	1.11 ± 0.04
τ_e	26.0 ± 2.0	28.5 ± 2.5	24.0 ± 1.2	30.5 ± 4.9
log $N_{\rm H}$ (cm^{-2})	21.8 ± 0.1	21.5 ± 0.2	21.95 ± 0.05	21.6 ± 0.2
Reducec χ^{2}[c]	1.33	0.67	0.45	1.22

[a] Quoted uncertainties are single-parameter 90% confidence limit.
[b] In a unit of 10^{-3} photons s^{-1} cm^{-2} keV^{-1}.
[c] For 17 degrees of freedom.

TABLE 4

SPECTRAL FITTING WITH THE GRAD MODEL ($i = 60°$) PLUS A POWER-LAW FUNCTION[a,b]

Parameter	1988 Jan
M ($M_\odot$)	5.52 ± 0.06
$\dot{M}$ (10^{18} g s^{-1})	5.38 ± 0.05
N_{power}[c]	0.65 ± 0.02
Photon index	2.21 ± 0.09
log N_H (cm^{-2})	21.2 ± 0.1
Reduced χ^2[d]	0.58

[a] Quoted uncertainties are single-parameter 90% confidence limit.
[b] Distance to the source is assumed to be 55 kpc.
[c] Photons s^{-1} keV^{-1} at 10 keV.
[d] For 19 degrees of freedom.

~20% of the total below ~9 keV when strongest, but in some cases it could not be detected at all.

3. DISCUSSION

We have found a characteristic spectral variation of LMC X-3 accompanying intensity variations by a factor of ~4. The soft spectral component, which is dominant below ~9 keV, shows clear correlation between the intensity and the hardness, while the hard component, which is conspicuous above that energy, varies independently from the soft component. The spectral variation of the soft component is well described by an optically thick accretion disk model with a remarkable constant innermost radius and variable mass accretion rate. The hard component is represented by a power-law function with the photon index ~2.2.

Very similar spectral characteristics are also found from newly discovered black hole candidates GS2000+25 (Tanaka 1989; Takizawa 1991; Ebisawa 1991) and GS1124−68 (Nova Muscae 1991) (Ogawa 1992) when the sources are in the soft spectral state. Constant innermost radii of the optically thick accretion disks and independently variable hard components is likely to be a common characteristic of black hole candidates in the soft spectral state.

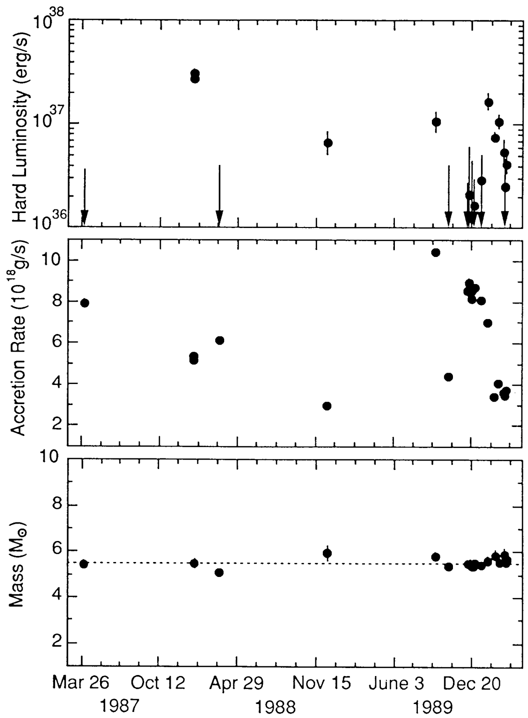

FIG. 3.—Summary of the spectral fitting of LMC X-3 with the GRAD model. The parameters of the GRAD model (mass of the compact object and mass accretion rate) and the luminosity of the power-law component (2–30 keV; the distance to the source is set to be 55 kpc and isotropic emission is assumed) are shown against date. The horizontal dotted line in the bottom panel indicates $M = 5.5\ M_\odot$.

The ~198 day periodicity in X-rays and optical light (Paper I) can be ascribed to periodic variation of the mass accretion rate, although the origin of the mass accretion rate change is as yet unclear. The X-ray variability is delayed by ~20 days relative to that of the optical light (Paper I). This delay may corre-

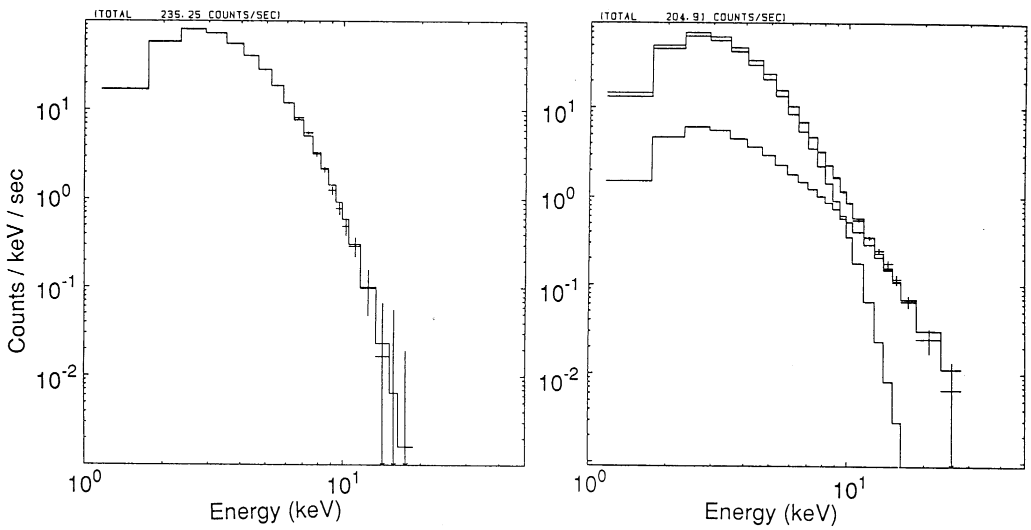

FIG. 2a FIG. 2b

FIG. 2.—Energy spectra of LMC X-3 without a hard-tail component (a; 1988 March) and with the strongest hard-tail component (b; 1988 January). The spectrum (a) is fitted with the GRAD model with the inclination angle 60°, and the spectrum (b) is fitted with the GRAD model plus a power-law function for the hard-tail component.

TABLE 5

SPECTRAL FITTING WITH THE GRAD MODEL ($i = 60°$) PLUS A POWER-LAW FUNCTION[a,b,c]

Parameter	1988 Jan	1988 Dec	1989 Sep	1989 Dec 9	Dec 14	Dec 21	Dec 27
M ($M_\odot$)	5.48 ± 0.22	5.97 ± 0.37	5.80 ± 0.13	5.50 ± 0.11	5.49 ± 0.17	5.37 ± 0.07	5.53 ± 0.06
$\dot{M}$ (10^{18} g s^{-1})	5.14 ± 0.10	2.96 ± 0.11	10.47 ± 0.13	8.54 ± 0.13	8.93 ± 0.19	8.55 ± 0.08	8.68 ± 0.04
N_{power}[d]	0.73 ± 0.06	0.16 ± 0.04	0.25 ± 0.06	<0.04	0.05 ± 0.09	<0.06	0.04 ± 0.03
log N_H (cm^{-2})	21.3 ± 0.1	21.3 ± 0.2	21.6 ± 0.1	21.4 ± 0.1	21.4 ± 0.1	21.5 ± 0.1	21.5 ± 0.1
Reduced χ^2[e]	1.01	1.39	2.48	0.84	1.14	1.05	2.66

Parameter	1990 Jan 12	Jan 28	Feb 16	Feb 26	Mar 12	Mar 15	Mar 18
M ($M_\odot$)	5.46 ± 0.12	5.60 ± 0.19	5.86 ± 0.23	5.58 ± 0.22	5.92 ± 0.25	5.57 ± 0.14	5.68 ± 0.15
$\dot{M}$ (10^{18} g s^{-1})	8.09 ± 0.11	7.05 ± 0.13	3.46 ± 0.10	4.09 ± 0.15	3.64 ± 0.10	3.52 ± 0.06	3.75 ± 0.07
N_{power}[d]	0.07 ± 0.05	0.39 ± 0.07	0.18 ± 0.02	0.25 ± 0.04	0.13 ± 0.04	0.06 ± 0.05	0.10 ± 0.02
log N_H (cm^{-2})	21.4 ± 0.1	21.5 ± 0.1	21.5 ± 0.1	21.5 ± 0.1	21.4 ± 0.1	<20.6	21.2 ± 0.1
Reduced χ^2[e]	0.77	1.47	0.98	0.80	0.58	0.84	0.85

[a] Quoted uncertainties are single-parameter 90% confidence limit.
[b] Distance to the source is assumed to be 55 kpc.
[c] The photon index of the power-law function is fixed to 2.21.
[d] Photons s^{-1} keV^{-1} at 10 keV.
[e] For 17 degrees of freedom.

spond to the time for accreting matter to drift from the outer optical emitting region to the inner X-ray emitting part.

The constancy of the innermost radius of the optically thick accretion disk against the significant mass accretion rate variations suggests that the innermost radius is related to the mass of the central object. The GRAD model used in the present analysis assumes the innermost radius to be 3 times the Schwarzschild radius of the central object. The mass of the central object derived by applying the GRAD model to the spectra depends on the distance to the source, the inclination angle of the disk, and the ratio of the color to the effective temperature of the emission. The average of the mass thus derived for LMC X-3 is

$$M \simeq 5.5\left(\frac{d}{55\ \mathrm{kpc}}\right)\left(\frac{T_{col}/T_{eff}}{1.5}\right)^2 f(60°)\ M_\odot\ .$$

The function $f(i)$ describes dependence of M on the inclination angle. This function increases with i; for $i = 0°$, 60°, and 70°, $f(i) = 0.46$, 1, and 1.16, respectively (Ebisawa et al. 1991; Ebisawa 1991). Note that the upper limit of the inclination angle imposed by the absence of an X-ray eclipse is 70° (Cowley et al. 1983).

The uncertainty in M mainly arises from $f(i)$ and T_{col}/T_{eff}. The M varies by a factor of $\sim$2.5 according to the inclination angle. The value $T_{col}/T_{eff} = 1.5$ was adopted from calculations of bursting neutron star atmosphere, but this value has not been calculated exactly yet for accretion disks. Considering these uncertainties, it can be said that the mass of the central object in LMC X-3 derived here agrees satisfactorily with the lower limit of the mass determined by optical observations of the binary motion ($\sim$7 $M_\odot$; Cowley et al. 1983; Paczyński 1983).

Many authors have discussed the structure of the inner part of an accretion disk around a black hole. According to Shakura & Sunyaev (1973), the viscosity is assumed to be proportional to the total pressure, and the inner part of the disk is optically thick with respect to true absorption ($\tau_* \equiv (\tau_{abs}\tau_{sct})^{1/2} \gtrsim 1$), requiring $\alpha \lesssim 0.01$ for the presently obtained parameters $M \sim 5.5\ M_\odot$ and $\dot{M} \sim 5 \times 10^{18}$ g s^{-1}. On the other hand, if the viscosity is assumed to be proportional to only the gas pressure, $\tau_* \gtrsim 1$ holds in the inner part of the disk for all reasonable values of M, $\dot{M}$, and α (Stella & Rosner 1984). In this prescription of the viscosity, the inner part of the disk, which is necessarily radiation pressure-dominant, is stable against thermal and viscous instabilities (e.g., Shibazaki & Hoshi 1975; Hoshi 1985; Kakubari, Hoshi, & Asaoka 1989). In any case, an optically thick accretion disk can extend down to the innermost stable orbit around a black hole, and hence the assumptions in the GRAD model will be justified.

In contrast to the soft component, the hard, power-law component is considered to be emitted from a hot, optically thin region. Several models have been proposed to explain the power-law spectra in galactic black hole candidates (see, e.g., Liang & Nolan 1984; Fabian 1988 for a review). However, no models thus far proposed will satisfactorily explain the absence of a clear correlation of the hard component with the soft component (probably with the mass accretion rate). The much larger than dynamical time scales of variations of the hard component around the black hole is also a difficult problem. Absence of a correlation with the mass accretion rate and the long time scales of the variations will be an important key to elucidate the origin of the hard component.

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REFERENCES

Arnett, W. D., & Bowers, R. L. 1977, ApJS, 33, 415
Cowley, A. P., Crampton, D., Hutchings, J. B., Remillard, R., & Penfold, J. E. 1983, ApJ, 272, 118
Cowley, A. P., et al. 1991, ApJ, 381, L526 (Paper I)
Ebisawa, K. 1991, Ph.D. thesis, Tokyo University
Ebisawa, K., Mitsuda, K., & Hanawa, T. 1991, ApJ, 367, 213
Ebisuzaki, T., Hanawa, T., & Sugimoto, D. 1984, PASJ, 36, 551
Fabian, A. C. 1988, in Physics of Neutron Stars and Black Holes, ed. Y. Tanaka (Tokyo: Univ. Acad. Press), 191
Hanawa, T. 1989, ApJ, 341, 948
Hartle, J. B. 1978, Phys. Rep., 46, 201
Hoshi, R. 1985, in Galactic and Extragalactic Compact X-Ray Sources, ed. Y. Tanaka & W. H. G. Lewin (Tokyo: Institute of Space and Astronautical Science), 143

Kakubari, K., Hoshi, R., & Asaoka, I. 1989, PASJ, 22, 537
Kuiper, L., van Paradijs, J., & van der Klis M. 1988, A&A, 203, 79
Liang, E. P., & Nolan, P. L. 1984, Space Sci. Rev., 38, 353
London, R. A., Taam, R. E., & Howard, W. M. 1986, ApJ, 306, 170
Makishima, K., Maejima, Y., Mitsuda, K., Bradt, H. V., Remilard, R. A., Tuohy, I. R., Hoshi, R., & Nakagawa, M. 1986, ApJ, 308, 635
Mitsuda, K., et al. 1984, PASJ, 36, 741
Ogawa, M. 1992, M.S. thesis, Rikkyo University
Paczyński, B. 1983, ApJ, 273, L81
Rhoades, C. E., & Ruffini, R. 1974, Phys. Rev. Lett., 32, 324
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shibazaki, N., & Hoshi, R. 1975, Prog. Theor. Phys., 54, 1706
Stella, L., & Rosner, R. 1984, ApJ, 277, 312
Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 86, 121
Takizawa, M. 1991, M.S. thesis, Tokyo University
Tanaka, Y. 1989, Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy, Vol. 1, 3 (Paris: ESA)
Treves, A., Belloni, T., Bouchet, P., Falomo, R., Chiapetti, L., Maraschi, L., & Tanzi, E. G. 1988a, ApJ, 335, 142
Treves, A., Belloni, T., Chiappetti, L., Maraschi, L., Stella, L., Tanzi, E. G., & van der Klis, M. 1988b, ApJ, 325, 119
Treves, A., et al. 1990, ApJ, 364, 266
Turner, M. J. L. 1989, PASJ, 41, 345
Weisskopf, M. C., Kahn, S. M., Darbro, W. A., Elsner, R. F., Grindlay, J. E., Naranan, S., Sutherland, P. G., & Williams, A. C. 1983, ApJ, 274, L65
White, N. E., Kaluzienski, J. L., & Swank, J. H. 1984, in High Energy Transients in Astrophysics, ed. S. E. Woosley (AIP CP 115), 31
White, N. E., & Marshall, F. E. 1984, ApJ, 281, 354
White, N. E., Stella, L., & Parmar, A. N. 1988, ApJ, 324, 363