The black hole binary LMC X-3 is known to be variable on timescales of days to years. We investigate X-ray and ultraviolet variability in the system as a function of the 1.7 day binary phase using the Rossi X-Ray Timing Explorer (RXTE) from 1998 December. An abrupt 14% flux decrease, lasting nearly an entire orbit, is followed by a return to previous flux levels. This behavior occurs twice, at nearly the same binary phase, but it is not present in consecutive orbits. When the X-ray flux is at lower intensity, a periodic amplitude modulation of 7% is evident in data folded modulo the orbital period. The higher intensity data show weaker correlation with phase. This is the first report of X-ray variability at the orbital period of LMC X-3. Archival RXTE observations of LMC X-3 during a high-flux state in 1996 December show similar phase dependence. An ultraviolet light curve obtained with the High-Speed Photometer on board the Hubble Space Telescope shows orbital modulation consistent with that in the optical, caused by the ellipsoidal variation of the spatially deformed companion.

The X-ray spectrum of LMC X-3 can be acceptably represented by a phenomenological disk black-body plus a power law. Changes in the spectrum of LMC X-3 during our observations are compatible with earlier observations during which variations in the 2–10 keV flux are tracked closely by the disk geometry spectral model parameter.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (LMC X-3) — X-rays: stars

1. INTRODUCTION

LMC X-3, a bright (up to $3 \times 10^{38}$ erg s$^{-1}$) black hole candidate in the Large Magellanic Cloud, is a highly variable X-ray source. It exhibits at least two distinct emission states. During its more common high/soft state, the X-ray spectrum is similar to that of other high/soft-state black hole candidates, with an "ultrasoft" component and a hard (>10 keV) tail. The low/hard state, on the other hand, is characterized by an X-ray spectrum described by a pure power law $I(E) = A \nu^{-\Gamma}$ with $\Gamma$ ~ 1.8 or less (Wilms et al. 2001), significant time variability with 30%–50% modulation of the intensity, and a 0.4 Hz quasi-periodic oscillation (OPO; Boyd et al. 2000).

The B3 V optical counterpart of LMC X-3 (Warren & Penfold 1975) ($V \sim 16.7$–17.5) shows a large velocity range (semiamplitude $K = 235$ km s$^{-1}$) through its 1.7 day orbital period. The lack of eclipses indicates that the inclination of the system is less than 70°, and this leads to a compact object mass of $\sim 7 M_\odot$ making LMC X-3 a prime black hole candidate (Cowley, Crampton, & Hutchings 1983; Paczyński 1983; Ebisawa et al. 1993; but see also Mazeh et al. 1986). The optical light curve shows minima at the times of conjunction of the two components, with amplitude $\sim 0.2$ mag each; the approximately equal minima of the optical light curve are consistent with an underlying ellipsoidal stellar surface (van der Klis et al. 1985). Comparing observations of the source over a long time baseline, it is apparent that the ratio of optical–to–X-ray flux is not constant. This may indicate secular variation of the disk structure over a timescale of a week or a change in anisotropy of the X-ray emission (Treves et al. 1990).

The long-term X-ray luminosity of the system is strongly modulated on timescales of hundreds of days (Cowley et al. 1991; Wilms et al. 2001). The mean 2–10 keV X-ray flux varies by a factor of more than 100 during this long-term cycle. This variability was previously attributed to the precession of a bright, tilted, and warped accretion disk. The discovery of recurrent low/hard states in LMC X-3 argues against this mechanism being responsible for the long-term variation (Wilms et al. 2001).

Previous X-ray observations have detected no phase-related variability in LMC X-3, and the 1.7 day orbital period is not detected prominently in the RXTE all-sky monitor (ASM) light curve. However, the Ginga and EXOSAT observations of this source were quite fragmentary—seven observations with durations ranging from 1 to 24 ks between 1983 December and 1984 December with EXOSAT (Treves et al. 1988), and a series of much shorter exposures spread over 3 yr with Ginga (Cowley et al. 1991). Prior to the launch of RXTE, no intensive study of LMC X-3 sampling an entire binary cycle in a single epoch had ever been performed. We thus proposed an RXTE observation to create a large set of data covering several consecutive orbital cycles with the minimum of interruptions. We present here the results obtained from this observation, performed in 1998 December, along with a reanalysis of archival data from a shorter dedicated RXTE pointing 2 yr earlier. We also include previously unpublished data from the High Speed Photometer (HSP) on
board *Hubble Space Telescope (HST)*, which is, to our knowledge, the only ultraviolet data on this source covering the 1.7 day binary orbit.

2. OBSERVATIONS

We observed LMC X-3 with *RXTE* (Bradt, Rothschild, & Swank 1993) between 1998 December 8 17:17 UT and December 15 00:01 UT, for an on-source total good time of 283 ks. These observations are summarized in Table 1. The data presented here were obtained using the Proportional Counter Array (PCA) instrument in the Standard 2 and Good Xenon data modes, with time resolutions of 16 s and less than 1 μs, respectively. The PCA consists of five Xe proportional counter units (PCUs), with a combined effective area of about 6500 cm\(^2\) (Jahoda et al. 1996). Only three of the five PCUs were on through the entire observation; we analyzed data only from these three detectors.

Spectra and light curves were extracted using the *RXTE* standard data analysis software, FTOOLS 5.0. The PCA background subtraction was performed using the “L7-240” (v19990824/0909) faint source model. LMC X-3 is reliably detected above background out to about 18 keV. Response matrices were generated using PCARSP 2.43 in FTOOLS 5.0, with the latest energy-to-channel relationship. Spectral fitting was performed using XSPEC 11.0.

The optical counterpart of the X-ray source LMC X-3 was observed with the polarimetric detector of the HSP on *HST* at six different orbital phases during the same binary orbit on 1993 August 24 12:09 UT and August 25 21:53 UT. The observations were obtained in the F277M bandpass using a 0.65 diameter aperture. The FWHM response of the F277M filter to a flat incident spectrum is 2600 using a diameter aperture. The FWHM response of the 0.65 diameter aperture was near 3 counts s\(^{-1}\).

The long-term light curve of LMC X-3 as measured by the ASM on board *RXTE* is shown in Figure 1, where the 4 day average count rate is plotted against the Julian Date. The long-term intensity variation is apparent and clearly not strictly periodic. The vertical lines denote the epochs of the pointed PCA observations discussed in this paper. We first turn our attention to the later of these, which began on 1998 December 8 17:17 UT. This observation was a short 16.2 minute exposure, but the source was observed for over 3 minutes.

![Figure 1](chart.png)

**Figure 1.**—Long-term variation of LMC X-3 as observed by the *RXTE* ASM. The 4 day average count rate is plotted against the Julian Date. Not strictly periodic, the episodes have timescales from 64 to 292 days. The vertical lines denote the epochs of the pointed PCA observations discussed in this paper.

TABLE 1

| Observation | Start MJD | Exposure Time (s) | Orbital Phase | Rate (counts s\(^{-1}\)) |
|-------------|-----------|-------------------|---------------|-------------------------|
| 1           | 51,155.719 | 17,032.0          | 0.765         | 74.30                   |
| 2           | 51,156.042 | 10,592.0          | 0.955         | 75.77                   |
| 3           | 51,156.516 | 2762.0            | 0.232         | 74.36                   |
| 4           | 51,156.633 | 12,16.0           | 0.301         | 75.89                   |
| 5           | 51,156.700 | 14,248.0          | 0.340         | 74.95                   |
| 6           | 51,156.993 | 11,208.0          | 0.512         | 74.10                   |
| 7           | 51,157.512 | 1920.0            | 0.816         | 75.04                   |
| 8           | 51,157.633 | 1368.0            | 0.887         | 76.71                   |
| 9           | 51,157.701 | 16,404.0          | 0.929         | 76.18                   |
| 10          | 51,158.000 | 15,355.0          | 0.103         | 74.01                   |
| 11          | 51,158.422 | 12,740.0          | 0.350         | 68.18                   |
| 12          | 51,158.710 | 14,058.0          | 0.520         | 67.62                   |
| 13          | 51,158.970 | 18,031.0          | 0.671         | 67.89                   |
| 14          | 51,159.242 | 1340.0            | 0.831         | 69.08                   |
| 15          | 51,159.421 | 11,099.0          | 0.937         | 69.47                   |
| 16          | 51,159.710 | 14,266.0          | 0.106         | 71.14                   |
| 17          | 51,159.969 | 16,895.0          | 0.258         | 74.25                   |
| 18          | 51,160.241 | 1664.0            | 0.478         | 75.51                   |
| 19          | 51,160.309 | 1536.0            | 0.457         | 76.03                   |
| 20          | 51,160.381 | 14,087.0          | 0.500         | 74.86                   |
| 21          | 51,160.710 | 14,749.0          | 0.693         | 73.89                   |
| 22          | 51,160.967 | 17,920.0          | 0.844         | 74.36                   |
| 23          | 51,161.709 | 22,855.0          | 0.280         | 67.89                   |
| 24          | 51,162.042 | 12,544.0          | 0.474         | 66.54                   |
JD 2,451,155, at the moderately faint average ASM rate of \( \sim 1 \text{ count s}^{-1} \). Our RXTE PCA light curve of LMC X-3 is shown in Figure 2. The entire 6.4 day coverage of our observing campaign is shown, along with 1 \( \sigma \) error bars. The PCA rate in counts per second is plotted against time in days (upper axis) as well as running binary phase (lower axis). The orbital phase is calculated using the van der Klis et al. (1985) ephemeris, namely, \( T_0 = \text{HJD} 2,445,278.005 + 1.70479 \times N \). Phase zero corresponds to superior conjunction of the X-ray source. The observations cover the \( \sim 3.5 \) consecutive binary orbits nearly uniformly, with only a few short gaps during this time.

### 3.1. Abrupt Flux Transitions

It is apparent in Figure 2 that there are two relatively flat stretches where the PCA rate stays near \( \sim 75 \text{ counts s}^{-1} \) for about one binary orbit, each of which abruptly ends with a flux decrease of \( \sim 14\% \) to a rate of \( \sim 66 \text{ counts s}^{-1} \). At each downward transition, the flux moves from the higher rate to the lower rate over a duration of \( \leq 0.42 \) days. The one upward and two downward transitions occur at similar binary phases. The time at which the first downward transition crosses the value of 70 counts s\(^{-1}\) is \( \sim \text{MJD 51,158.15, phase 0.19} \). The time at which the upward transition crosses this level (on its return to the “nominal” flux level) is \( \sim \text{MJD 51,159.85, again binary phase 0.19—very nearly one integer binary orbit later} \). While the coverage gap immediately preceding the second downward transition makes the measured onset time uncertain (see Fig. 2), we estimate it begins at or before \( \sim \text{MJD 51,161.74, phase 0.29} \). In other words, the cycle from one downward transition to the next repeats at very nearly twice the orbital period. This is interesting for it implies that the mechanism giving rise to the abrupt flux transitions is dynamically linked to the orbit.

### 3.2. Orbital Phase Dependence of X-Ray Flux

We searched for evidence of X-ray modulation at the orbital period by dividing the data into two groups based on source count rate. Data with a rate below 70 counts s\(^{-1}\) were folded on the orbital period separately from those points with rate above 70 counts s\(^{-1}\), thus preventing the gross flux transitions discussed above from contaminating the folded light curves. (Taking the data set as a whole and folding on the orbital period would result in data from higher and lower gross flux segments being averaged together in a single phase bin, which masks the lower amplitude phase modulation.)

Figure 3 shows the results of folding each of these data sets on the orbital period of the van der Klis et al. (1985) ephemeris. The orbital modulation is clear in the low-flux data (Fig. 3a)—it reaches a maximum slightly beyond \( \phi = 0.0 \), while the minimum occurs near \( \phi = 0.5 \). Folding the high-flux data (Fig. 3b) at the orbital period shows apparently weaker phase modulation.

To further investigate the presence of phase-dependent flux variability, we performed periodogram analysis on the data set as a whole, binned at 800 s, and the phase-selected subsets defined above. We restricted the period search to the higher rate data (Fig. 3b) at the orbital period shows apparently weaker phase modulation.

![Fig. 2.—PCA light curve of LMC X-3 vs. phase (lower x-axis) and time in MJD (upper x-axis) from 1998 December.](image1)

![Fig. 3.—PCA light curve from the 1998 December observations, folded on the 1.7 day binary period. The top panel includes only data where the rate is less than 70 counts s\(^{-1}\); at these lower fluxes, the amplitude of the orbital variation is 7%. The lower panel shows the folded higher flux data (\( > 70 \text{ counts s}^{-1} \)). Phase variability at this count rate is less significant. A sine wave with the same period and phase has been superposed on each plot to guide the eye.](image2)
within 0.5 days of the observed orbital period. Significance was estimated using the false-alarm probability defined by Scargle (1982). The best-fit trial period of the low-flux data is \(1.693 \pm 0.037\) days, with a false-alarm probability of \(2.4 \times 10^{-14}\) for a greater than 7 \(\sigma\) detection. The best-fit trial period for the high-flux data is \(1.712 \pm 0.037\) days, with false alarm probability of \(4.5 \times 10^{-11}\) for a greater than 6 \(\sigma\) detection. Each detection is significant and consistent with the observed orbital period in the optical. We conclude that significant periodic amplitude modulation is present in the X-ray flux from LMC X-3 and that the amplitude of the modulation is slightly higher when the 2–10 keV flux is lower. This is the first reported detection of orbital phase dependence in the X-ray intensity from LMC X-3.

3.3. Archival RXTE Observations During a High/Soft State

Nowak et al. (2001) discuss a previous 140 ks RXTE observation of LMC X-3 obtained during 1996 November 30–December 6 when the source was at the relatively high RXTE/ASM count rate of about 3.5 counts s\(^{-1}\). Their light curve (Fig. 1 of Nowak et al. 2001) shows similar qualitative behavior: a slow flux transition from higher rate to lower rate in the 2–10 keV flux with an overall amplitude \(\sim 12\%\). Motivated by the detection of strong phase dependence in LMC X-3 at relatively low flux levels, we extracted this archival data set to search for orbital modulation at a significantly different flux level and epoch. Since different detectors were on/off through this observation, we scaled the light curve to the 5 PCU rate. Again, owing to the overall gross flux transition present during this long observation, we grouped their data into two segments, selected by total PCA rate (above/below 410 counts s\(^{-1}\)), before folding on the van der Klis et al. (1985) ephemeris. The results of this analysis are presented in Figure 4. Phase dependence is clearly present in both groups of data. The phase coverage of the observation when the source was at slightly greater flux levels is insufficient to trace out an entire cycle; only orbital phase \(\phi = 0.0–0.5\) was observed. At the lower count rate, the phase coverage is sufficient to trace out a light curve qualitatively similar to that seen in the low-flux 1998 December data. As in the 1998 December observation, it is single-peaked; the maximum X-ray intensity occurs near \(\phi = 0.95–0.05\) while the minimum is near \(\phi = 0.5\). As in the 1998 December data, the amplitude of this modulation is \(\sim 5\%\).

3.4. Searches for Rapid Time Variability

We searched for rapid aperiodic variability in LMC X-3 using the high time resolution PCA data obtained in the Good Xenon mode. Discrete power spectral density distributions (PSDs) were calculated by dividing the data into segments of uniform length, performing fast Fourier transforms of each, and averaging the results. The PSDs were normalized such that their integral gives the squared rms fractional variability (Miyamoto et al 1991; van der Klis 1989). We subtracted the Poisson noise level from the power spectra, taking into account the modifications expected from PCA detector dead time. In its low/hard state, LMC X-3 displays QPOs at a centroid frequency of 0.4 Hz and significant time variability of 30%–50% (Boyd et al. 2000). Neither are detected in this observation, and the long duration of this data set allows us to place a rather stringent upper limit of 1% on the rms amplitude of a QPO feature between 0.1 and 10 Hz.

3.5. Summary of Timing Results

Our analysis of the time variability in LMC X-3 indicates that the light curve shown in Figure 2 can be described as the superposition of (1) an orbital modulation of roughly constant amplitude and (2) abrupt flux transitions recurring at twice the orbital period. Significant orbital modulation is also present in archival data (Fig. 4) taken when LMC X-3 was at a dramatically different flux level, implying that orbital modulation is a reliable feature in the X-ray output through a fourfold range of source intensities. The 1996 December archival observation also contains one gross flux transition, although the data set is not long enough to determine whether it repeats, and if so, at what period. The amplitude of the orbital modulation in the 1996 December observation is approximately 5%, as in the 1998 December data.
Fig. 5.—UV light curve from HST obtained in 1993 (this paper, rectangles) superposed on the optical V light curve from 1984 (van Paradijs et al. 1987, circles). UV flux is given on the left-hand axis; V-band magnitude on the right-hand axis. The two scales are independent; their intervals were adjusted to give the same amplitude in each bandpass. While its phase coverage is sparse, the UV variability is consistent with the optical light curve.

4. HSP RESULTS: UV PHOTOMETRY AND POLARIMETRY

Orbital modulation of the X-ray flux has not been previously observed in LMC X-3, although it is a well-known feature of the optical light curve. In the V band, the ellipsoidal deformation of the B star results in the double-peaked morphology of the light curve. In an effort to extend our knowledge of the orbital modulation of LMC X-3 as a function of photon energy, we present the results of an ultraviolet photometric and polarimetric study of LMC X-3 using the HSP on board HST.

In Figure 5 we compare the orbital light curve we obtained in the F277M bandpass in 1993 with the V-band light curve obtained in 1984 by van Paradijs et al. (1987). While the phase coverage of the UV light curve is sparse, the overall variation is not inconsistent with the double-peaked optical light curve. The UV light curve is also consistent with an additional source of UV radiation in the system, with maximum occurring near inferior conjunction of the X-ray source. This second light would presumably be coming from the accretion disk.

No linear polarization was detected at any orbital phase (see Table 2). Assuming constant polarization from LMC X-3 in the F277M bandpass and treating the normalized Stokes parameters as normally distributed (but cf. Clarke et al. 1983), the 2 $\sigma$ upper limit on the linear polarization of LMC X-3 in the F277M bandpass is $p \leq 0.018$. Several other X-ray binary systems, notably Cygnus X-1, do show significant phase-dependent polarization in the UV, interpreted as evidence for single scattering off gas streams connecting the primary to the accretion disk (Dolan & Tapia 1988; Wolinski et al. 1996). The upper limit on any variable polarization is too large to contain any information about the structure of the gas streams in the system.

5. X-RAY SPECTRAL VARIABILITY

There is no single accepted model for the spectral variability of Galactic black hole candidates across their several spectral states (see reviews by Tanaka & Lewin 1995, Nowak 1995, and van der Klis 1995 for discussions of black hole spectral states). Numerous authors choose a phenomenological “disk blackbody plus power law” model, in which the spectrum is fit by the superposition of multiple rings of blackbodies representing the cooler accretion disk, plus a power law to describe the hard photons. While not motivated by a clear physical picture of what gives rise to these independent components, this model does give reasonable results for spectral fits (although commonly a “feature” is seen at the crossover point of the two functions). Alternative models based on a physical description of the interaction of a spherical Comptonizing corona and cooler seed photons from the disk (Shrader & Titarchuk 1999; Borozdin et al. 1999) are often applicable only in restricted spectral states or produce biased residuals at high energies. Because previous spectral studies of LMC X-3 have concentrated on the phenomenological disk–blackbody plus power law model (Wilms et al. 2001; Nowak et al. 2001, also Ebisawa et al. 1993; Cowley et al. 1991), and because of the ambiguity in the spectral state of LMC X-3 at this relatively low flux level, we have chosen to report our spectral fitting results using this model. In the following discussion, model parameters for the power-law component are photon index $\Gamma$ and $A_{\text{ph}}$ in photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. The disk blackbody model is parameterized by $T_{\text{in}}$, the temperature (kT) at the inner edge of the accretion disk, as well as a geometric factor $N$, which depends on the inner disk radius, the viewing angle of the accretion disk, and the distance to the source.

Wilms et al. (2001) report recurrent low/hard states in LMC X-3 based on long-term monitoring with RXTE over several years. This was confirmed by more recent RXTE observations during a low/hard state (Boyd et al. 2000) in which both the timing and spectral characteristics of black hole candidates in the low/hard state was observed. Wilms et al. (2001) report a disk temperature that drops below 1.0 keV as the source enters the low state. The source is well described by a pure power law with $\Gamma = 1.7$ when truly in the low state.

In our investigation of the spectral changes during our observation, we restrict ourselves to data obtained far from the South Atlantic Anomaly passage and with low measured electron contamination. We consider only observations where the orbital phase was between 0.475 and 0.525 in an attempt to minimize orbital effects when comparing the higher flux and lower flux spectra. Our spectral fits include data from 2.5 to 25.0 keV. The power law plus blackbody disk model was found to be acceptable under the $\chi^2$ test for each individual spectrum, with typical

| Orbital Phase | Flux (mJy) | Polarization |
|---------------|-----------|--------------|
| 0.655-0.687… | 0.485 ± 0.012 | 0.016 ± 0.018 |
| 0.835-0.891… | 0.452 ± 0.012 | 0.014 ± 0.024 |
| 0.934-0.981… | 0.402 ± 0.011 | 0.000 ± 0.030 |
| 0.127-0.161… | 0.451 ± 0.012 | 0.000 ± 0.022 |
| 0.334-0.389… | 0.549 ± 0.013 | 0.000 ± 0.021 |
| 0.423-0.480… | 0.506 ± 0.012 | 0.017 ± 0.017 |
December observations follow the short-timescale trend fairly constant while the disk temperature exhibits marked long-term trends, wherein the normalization term remains spectral components run counter to previously observed variation in 1996 December, variations in the disk blackbody one binary cycle to the next.

Reduced $\chi^2$-values near or below 1.0 for 49 degrees of freedom.

Results of spectral fits to the $\phi = 0.5$ observations are summarized in Table 3. A typical two-component model fit is shown in Figure 6. The disk temperature hovers near the critical value of $kT = 1.0$, reported by Wilms et al. (2001) as an indicator of the occurrence of a transition from the high/soft to the low/hard state. Unlike the pure low/hard state, however, a significant disk component is required to achieve a reasonable spectral fit to the current observations. This may indicate that LMC X-3 was undergoing a state transition at the time. The model flux reported in Table 3 is about 15 times greater than the flux measured during the 2000 May low/hard state (Boyd et al. 2000).

The disk blackbody spectral components show a roughly linear trend with the $2 - 10$ keV flux. The changes in $T_{\text{in}}$ are small and within the formal uncertainties on this parameter. On the other hand, the disk normalization parameter $N$ varies by $\sim 20\%$ from minimum to maximum flux. Since $N$ is proportional to $r_{\text{in}}^2 \cos \theta$, it implies either a change in the inner accretion disk radius or the inclination of the disk is responsible for the gross flux variation from one cycle to the next. A global warp or kink, traveling around the disk, could cause the effective inclination of the disk to vary from one binary cycle to the next.

Nowak et al. (2001) point out that during the long observation in 1996 December, variations in the disk blackbody spectral components run counter to previously observed long-term trends, wherein the normalization term remains fairly constant while the disk temperature exhibits marked variability with observed flux. Our results of the 1998 December observations follow the short-timescale trend found by Nowak et al. (2001), where the disk blackbody temperature is relatively constrained and variability is instead correlated to the geometric normalization parameter.

6. DISCUSSION AND CONCLUSIONS

Our RXTE observations of LMC X-3 through 3.5 consecutive binary cycles have detected significant orbital phase modulation of the $2 - 10$ keV X-ray flux. The amplitude of the orbital modulation is variable, being higher when the system experienced an abrupt decrease in flux. Comparison of our results to an archival observation at a profoundly different flux level shows that phase-dependent flux is a hallmark of LMC X-3 through a wide range of overall X-ray intensities, with an amplitude of between 5\% and 10\%. The UV light curve, while sparse, is consistent in shape with the optical variability, implying that the dominant component of the UV radiation is the deformed main-sequence star and outer disk, as in the optical.

A phase-dependent X-ray flux may be due to (1) a compact “hot spot” of X-ray generation moving into and out of our line of sight, (2) a region of cooler absorbing matter moving into and out of our line of sight, or (3) a combination of the two. Since LMC X-3 does not display eclipses of the compact object, its inclination is not well constrained. A possible geometric model that explains the variation seen at the different flux levels is that of a hot spot located between the main-sequence star and the compact object, perhaps where the stream impacts the accretion disk. X-rays from this hot spot could be absorbed by the accretion disk at inferior conjunction of the X-ray source ($\phi = 0.5$) but be visible to the observer at superior conjunction ($\phi = 0$). The expected curvature of the gas stream would give rise to the flux maximum occurring slightly after superior conjunction. Changes in the location of the gas stream as a function of mass accretion rate could account for the slightly different phase of maximum during the high-state 1996 observations.

An equally striking feature of our RXTE light curve is the abrupt flux decreases, separated by nearly very binary periods. The slower return to the higher flux level also occurs near similar binary phase. One possible model for the system that explains both the overall flux transitions and the variable orbital phase modulation is that of a disk excited into a low-order global mode. Global instabilities in highly ionized accretion disks around compact objects are not sufficiently well understood to claim that this model is realistic or expected. However, there is growing numerical and observational evidence that suggests similar global structures in accretion disks do develop and persist. Such a large-scale perturbation of the accretion disk provides a global mechanism for angular momentum transport and dispersion, which, together with the local viscous processes,
can drive the dynamics of the disk. Evidence for significant two-armed spiral structure has been seen in Doppler tomography studies of the dwarf nova IP Pegasi during two outbursts (Steeghs 2000). Three-dimensional hydrodynamic simulations of accretion disks show that the formation of spiral shocks is common over a wide range of system parameters, including disk temperatures much hotter than those in dwarf novae (Boffin, Haraguchi, & Matsuda 1999).

We suggest the presence of a global density wave in the accretion disk of LMC X-3 as one possible explanation that is consistent with the data. If such a global feature were stable for several binary orbits and rotated with an angular velocity close to one quarter the orbital velocity, then the gross features in the X-ray light curve would be reproduced because of the varying obscuration along the line of sight. As the feature rotated around the disk, it would at times obscure observed X-rays in a phase-dependent fashion and at other times have little appreciable effect on the observed X-ray flux. This concept is illustrated schematically in Figure 7, where we represent the global mode as a spiral density wave. We do not rule out other combinations of disk and orbital geometry that may explain the observed behavior. We note, however, that the spiral structure seen in IP Peg, as well as large-scale disk asymmetries in other systems, have been observed to corotate with the binary system.

The long-term variability of LMC X-3 is not easily characterized. It is becoming clear that the previous conjecture of periodic large-amplitude flux variations arising from a warped precessing disk is not complete: the large-scale variation seen in the RXTE ASM (Fig. 1) is far from simply periodic. If instead its long-term behavior is similar to Cygnus X-1 and other persistent Galactic black hole candidates, then LMC X-3 stands out owing to the suggestion of a preferred timescale on the order of hundreds of days from one low/hard state to the next. If a global disk instability is responsible for state transitions in such systems, then the disk dynamics in LMC X-3 must be quite different from the persistent Galactic black holes, which apparently undergo the transition in a more random fashion. It is possible that LMC X-3 does not fit neatly into either category above but has characteristics of each. In that case, continued intensive studies of the system should be carried out with the goal of developing a consistent physical model of the accretion disk structure and dynamics.

This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by NASA’s Goddard Space Flight Center. ASM results were provided by the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA’s GSFC. Based in part on observations with the Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract NAS5-26555. We enjoyed helpful conversations with Mike Nowak and Joern Wilms. Karen Smale produced the artwork in Figure 7.

Fig. 7.—Schematic representation of a low-order global oscillation mode excited in an accretion disk. If such a feature were stable for several binary orbits and rotated with an angular velocity close to one quarter the orbital velocity, then the gross features in the X-ray light curve would be reproduced because of the varying obscuration along the line of sight.

REFERENCES

Bless, R. C., et al. 1999, PASP, 111, 364
Boffin, H. M. J., Haraguchi, K., & Matsuda, T. 1999, in Disk Instabilities in Close Binaries—25 Years of the Disk-Instability Model, ed. S. Mine-
shige, & J. C. Wheeler (Tokyo: Univ. Acad.), 137
Borozdin, K., Revnivtsev, M., Trudolyubov, S., Shrader, C. R., & Titarchuk, L. G. 1999, ApJ, 517, 367
Boyd, P. T., Smale, A. P., Homan, J., Jonker, P. G., van der Klis, M., & Kuulkers, E. 2000, ApJ, 542, L127
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Clarke, D., Stewart, B. G., Schwarz, H. E., & Brookes, A. 1983, A&A, 126, 260
Cowley, A. P., Crampton, D., & Hutchings, J. B. 1983, ApJ, 272, 118
Cowley, A. P., et al. 1991, ApJ, 381, 526
Dolan, J. F., et al. 1994, ApJ, 432, 560
Dolan, J. F., & Tapia, S. 1986, PASP, 98, 792
——– 1988, A&A, 202, 124
Ebisawa, K., Makino, F., Mittakuda, K., Belloni, T., Cowley, A. P., Schmidke, P. C., & Treves, A. 1993, ApJ, 403, 684
Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., & Morgan, E. H. 1996, in EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VII, ed. O. H. Siegmund (Bellingham: SPIE), 59
Mazeh, T., van Paradijs, J., van den Heuvel, E. P. J., & Savonije, G. H. 1986, A&A, 157, 113
Miyamoto, S., Kimura, K., Kitamoto, S., Dotani, T., & Ebisawa, K. 1991, ApJ, 383, 784
Nowak, M. A. 1995, PASP, 107, 1207
Nowak, M. A., Wilms, J., Heindl, W. A., Pottschmidt, K., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 316
Paczyński, B. 1983, ApJ, 273, L81
Scargle, J. D. 1982, ApJ, 263, 835
Shrader, C. R., & Titarchuk, L. 1999, ApJ, 521, L121
Simmons, J. F. L., & Stewart, B. G. 1985, A&A, 142, 100
Steeghs, D. 2000, in prepprint (astro-ph/0012153)
Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
Treves, A., et al. 1988, ApJ, 325, 119
——–, 1990, ApJ, 364, 266
van der Klis, M. 1989, ARA&A, 27, 517
——–, 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252
van der Klis, M., Clausen, J. V., Jensen, K., Tjemkes, J., & van Paradijs, J. 1985, A&A, 151, 322
van Paradijs, J., van der Klis, M., Augusteijn, T., Charles, P., Corbet, R. H. D., et al. 1987, A&A, 184, 201
Wardle, J. F. & Kronberg, P. P. 1974, ApJ, 194, 249
Warren, P. R., & Penfold, J. E. 1975, MNRAS, 172, 41P
Wilms, J., Nowak, M. A., Pottschmidt, K., Heindl, W. A., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 327
Wolinski, K. G., et al. 1996, ApJ, 457, 859

—. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252

van der Klis, M., Clausen, J. V., Jensen, K., Tjemkes, J., & van Paradijs, J. 1985, A&A, 151, 322

van Paradijs, J., van der Klis, M., Augusteijn, T., Charles, P., Corbet, R. H. D., et al. 1987, A&A, 184, 201

Wardle, J. F. & Kronberg, P. P. 1974, ApJ, 194, 249

Warren, P. R., & Penfold, J. E. 1975, MNRAS, 172, 41P

Wilms, J., Nowak, M. A., Pottschmidt, K., Heindl, W. A., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 327

Wolinski, K. G., et al. 1996, ApJ, 457, 859

—. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252

van der Klis, M., Clausen, J. V., Jensen, K., Tjemkes, J., & van Paradijs, J. 1985, A&A, 151, 322

van Paradijs, J., van der Klis, M., Augusteijn, T., Charles, P., Corbet, R. H. D., et al. 1987, A&A, 184, 201

Wardle, J. F. & Kronberg, P. P. 1974, ApJ, 194, 249

Warren, P. R., & Penfold, J. E. 1975, MNRAS, 172, 41P

Wilms, J., Nowak, M. A., Pottschmidt, K., Heindl, W. A., Dove, J. B., & Begelman, M. C. 2001, MNRAS, 320, 327

Wolinski, K. G., et al. 1996, ApJ, 457, 859