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SIMULTANEOUS X-RAY, ULTRAVIOLET, AND OPTICAL OBSERVATIONS OF LMC X-3

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ABSTRACT

The black hole candidate LMC X-3 was observed simultaneously at X-ray (*Ginga*), UV (*IUE*), and optical frequencies in 1988 January. The X-ray energy distribution is the superposition of a thermal component and a hard tail. The former component can be described equally well by a Comptonization spectrum or by a *disk blackbody*. In the latter picture, the high-energy tail may derive from the inner part of the accretion disk, which is hot and transparent. Optical and UV data indicate a very low state of the source. Comparing with 1984 observations, one finds that the optical-to-X-ray flux ratio is not maintained, possibly indicating a secular variation of the disk structure, or a change of the anisotropy of the X-ray emission.

Subject headings: black holes — radiation mechanism — stars: individual (LMC X-3) — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

LMC X-3 is a bright X-ray source at the periphery of the Large Magellanic Cloud, which was discovered with *Uhuru* (Leong *et al.* 1971). Subsequent observations with various satellites have shown the X-ray flux to vary up to a factor of 100, and the presence of an unusually soft X-ray spectrum (for references see, e.g., Treves *et al.* 1988*c*). The optical counterpart ($m_V \simeq 17$, Sp = B3 V) was first proposed by Warren and Penfold (1975). Cowley *et al.* (1983), on the basis of spectroscopy and photometry, discovered the binary period of the system ($P = 1^{\rm d}.7$). The measured mass function $f(M) = 2.3\ M_{\odot}$ suggests the presence of a $\sim 9\ M_{\odot}$ black hole in the system, which was later supported by arguments by Paczyński (1983), Kuiper, van Paradijs, and van der Klis (1988), Treves *et al.* (1988*a*), and Bochkarev *et al.* (1988).

In the visible the object appears to vary irregularly ($16.8 < V < 17.5$), with the superposed orbital modulation $\Delta V \simeq 0.15$ (van Paradijs *et al.* 1987). From the optical light curve and far-UV observations, the presence of a rather cool ($T = 1.4 \times 10^4$ K) accretion disk was derived (van Paradijs *et al.* 1987; Treves *et al.* 1988*a*). The disk screens off the noncollapsed component from X-ray heating, as indicated by the shape of the light curve. In turn, the disk is heated by the X-rays and its radiation in the optical and UV bands derives from X-ray reprocessing.

In order to further study this system and in particular the interactions between the various components, we organized in 1988 January simultaneous multiwavelength observations: in X-rays (*Ginga* satellite), in the UV (*International Ultraviolet Explorer*, hereafter *IUE*), and in the optical (1.5 m ESO telescope).

II. OBSERVATIONS

a) X-Ray Observations

i) *X-Ray Energy Distribution*

LMC X-3 was observed with the *Ginga* satellite on 1988 January 8–9 (see Table 1). The instruments on board *Ginga* are described in Makino (1987). The observations reported here refer to the large area proportional counter (LAC) of effective area $\simeq 4000$ cm^2, with sensitivity in the 1.5–30 keV energy range (Turner *et al.* 1989).

The observation was made with the MPC-1 and MPC-3 mode (Turner *et al.* 1989); the energy channels were 48 and 12, and the time resolution, 16 s and 7.8 ms, respectively. The exposures were intermittent, and the maximum continuous duration was about 30 minutes. The net exposure times for each mode were 24,000 and 9900 s. Background correction was evaluated by a direct measurement of the nearby sky, and from a model of the background (Hayashida *et al.* 1989). Good agreement between the two results was obtained.

Background corrected count rates in the 1.2–7.0 keV and 1.2–24 keV bands are plotted in Figure 1, together with the hardness ratios. Clearly the X-ray intensity exhibited little variation in any band. Short-term variability was examined by Fourier analysis (see the following section).

The X-ray spectrum for the superposition of the observations is shown in Figure 2. Significant signal is detected up to about 25 keV. The spectrum cannot be described by simple models (e.g., power-law, blackbody, or free-free). Acceptable fits are obtained, however, with more complex models, such as blackbody emission + power-law, a multitemperature disk blackbody (DBB) (see, e.g., Mitsuda *et al.* 1984) + power-law, the unsaturated Comptonization spectrum + power-law, or the Sunyaev-Titarchuck (1980) formula + power-law (see Table 2). The residuals from these fits do not show evidence for lines in the spectrum. The best-fit parameters, the 90% confidence uncertainties, and the reduced χ^2 for these fits are reported in Table 2. The approximate deconvolution of the spectra for the case DBB + power-law is shown in Figure 3. In the 2–8 keV range, the spectrum is close to that observed with *EXOSAT* in 1984 December 15.

An important result of the *Ginga* observations is the clear indication of a hard component, which shows up at energies

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TABLE 1

LMC X-3: OBSERVATIONS OF 1988 JANUARY

A. *Ginga*

Start Time (1988)		End Time	Exposure Time (minutes)	Observation Mode	Flux (2 keV)
Jan 8	05.00	07.44	50	MPC-1	
	07.50	14.50	160	MPC-3	0.062 photons
	15.48	07.52	420	MPC-1	cm^{-2} s^{-1} keV^{-1}
Jan 9	07.55	10.12	50	MPC-3	

B. *IUE*

Date (1988)	Spectrum Identification	λλ (Å)	Exposure Time (minutes)	Flux × 10^{-14} (ergs cm^{-2} s^{-1} $Å^{-1}$)
Jan 8, UT 10 15	LWP 12459	2400–3100	240	0.17 (2550A)
Jan 9, UT 7 52	SWP 32694	1200–1950	398	0.4 (1740)

C. ESO 1.5 m + B + C Spectrograph + CCD

Date (1988)	Spectrophotometry Identification	λλ (Å)	Exposure Time (s)	*B* (mag)	*V* (mag)
Jan 8, UT 03 27	14	4000–7300	3600	17.4	17.4
Jan 10:					
UT 03 30	29	4000–7300	2400	17.5	17.6
UT 04 10	30	4000–7300	1800	17.6	17.6
Jan 11, UT 06 07 ...	41	4000–7300	2400	17.4	17.5

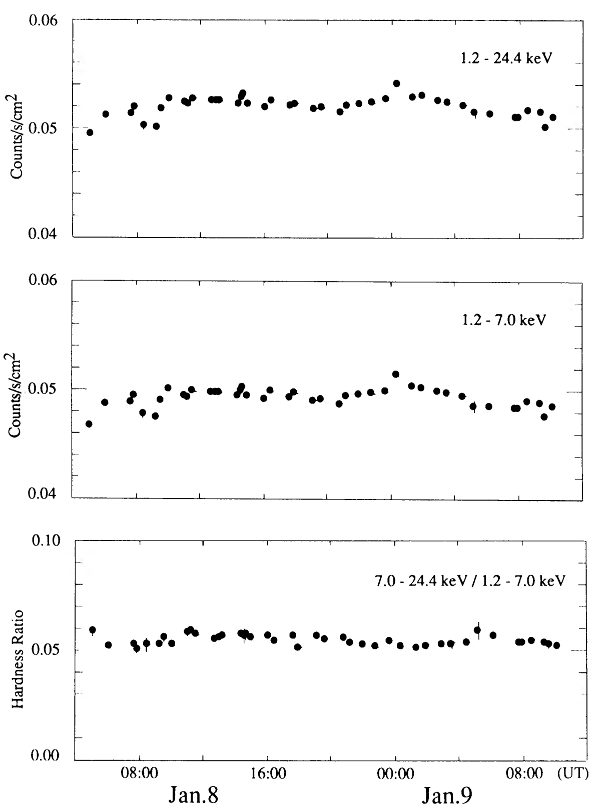

FIG. 1.—The X-ray light curves of LMC X-3 in two energy bands and hardness ratio observed with *Ginga* in 1988 January. The accumulation time for each data point is about 10 minutes.

about 8 keV. In the fits presented above, this is described as a power law of energy index 1.1–1.7. The hard component was not detected by *EXOSAT* because of the lower sensitivity of the instrumentation, while it appeared in *HEAO 1* A-2 data up to 15 keV (White and Marshall 1984).

ii) *X-Ray Power Spectra*

Power spectra were obtained from the MPC-3 mode data, binned in intervals of 256 s by fast Fourier transform. The

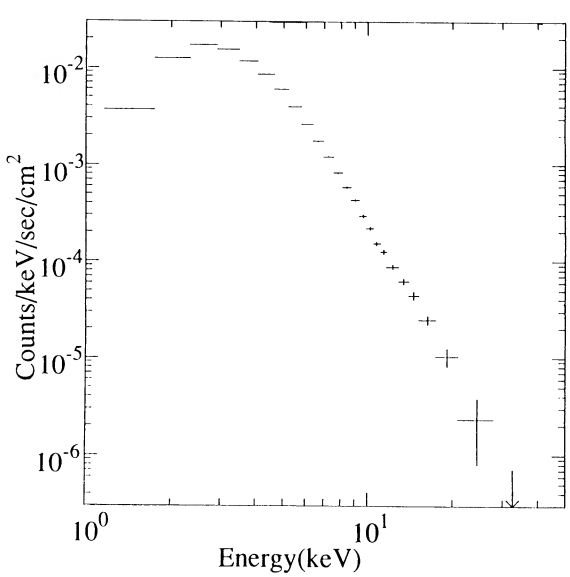

FIG. 2.—The pulse-height distribution of X-rays from LMC X-3 obtained with LAC on *Ginga*.

TABLE 2

BEST-FIT PARAMETERS

Parameter	Value
1. Disk-Blackbody + Power-Law	
$\left[\frac{dN}{dE} = \frac{8\pi}{3}\frac{r_{\rm in}^2}{d^2}\cos i \int_{T_{\rm out}}^{T_{\rm in}} \left(\frac{T}{T_{\rm in}}\right)^{-11/s} B(E, T)\frac{dT}{T_{\rm in}} + N_{\rm pl}E^{-\alpha}\right]$	
$\log N_{\rm H}$	$21.5^{+0.2}_{-0.5}$
$r_{\rm in}(\cos i)^{1/2}$	23.3 ± 0.7 km ($d = 50$ kpc)
$T_{\rm in}$	1.08 ± 0.01 keV
$N_{\rm pl}$	0.12 ± 0.01 photons cm^{-2} s^{-1} keV^{-1}
α	2.77 ± 0.65
$\chi^2/28$	0.82
2. Unsaturated Comptonization + Power-Law	
$\left[\frac{dN}{dE} = AE^{-\beta}\exp^{-E/kT} + N_{\rm pl}E^{-\alpha}\right]$	
$\log N_{\rm H}$	<21.4
A	0.28 ± 0.05 photons cm^{-2} s^{-1} keV^{-1}
β	0.2 ± 0.3
kT	$1.4^{+0.1}_{-0.2}$ keV
$N_{\rm pl}$	$0.020^{+0.045}_{-0.010}$ photons cm^{-2} s^{-1} keV^{-1}
α	$2.1^{+0.5}_{0.2}$
$\chi^2/27$	0.67
3. Sunyaev and Titarchuk + Power-Law	
$\left[\frac{dN}{dE} = N_C\left(\frac{E}{kT}\right)^2 \exp^{-E/kT}\int_0^\infty d\xi\,\xi^{n-1}\left(1-\xi\frac{kT}{E}\right)^{n+3}\exp^{-\xi} + N_{\rm pl}E^{-\alpha}\right]$	
n	$-\frac{3}{2} + \left(\gamma + \frac{9}{4}\right)^{1/2}$;
γ	$\frac{\pi^2}{3}\frac{m_e c^2}{(\tau + 2/3)^2 kT}$
$\log N_{\rm H}$	21.8 ± 0.1
N_C	0.011 ± 0.002
kT	1.01 ± 0.05 keV
τ	29 ± 5
$N_{\rm pl}$	$0.050^{+0.085}_{-0.025}$ photons cm^{-2} s^{-1} keV^{-1}
α	$2.4^{+0.4}_{-0.2}$
$\chi^2/27$	0.74

computation refers to the energy range 1–36 keV and covers the frequency range 4×10^{-3}–64 Hz. The resulting power spectrum, after subtraction of white noise due to counting statistics, is shown in Figure 4. Although the spectrum is quite noisy, it is apparent that power is present at least in the range 4×10^{-3}–50 Hz. The power spectrum can be fitted with a power law of index -1.1 ± 0.3 (reduced $\chi^2 = 1.25$ for d.o.f. = 25; the uncertainty represents 90% confidence). The variability was not large enough to derive energy dependence of the spectrum. The total rms fractional variation is 4.7 ± 0.4%. Treves *et al.* (1988*c*), on the basis of *EXOSAT* data, found an indication of a characteristic time scale of 600 s based on the exponential shape of the autocorrelation function, with a total rms of 1%. This noise component can be identified with the low-frequency part of the *Ginga* power spectrum.

b) IUE Observations

LMC X-3 was observed with *IUE* in the range 1200–3000 Å. Details are given in Table 1. Care was taken in eliminating regions where particle events or other flaws were present. The

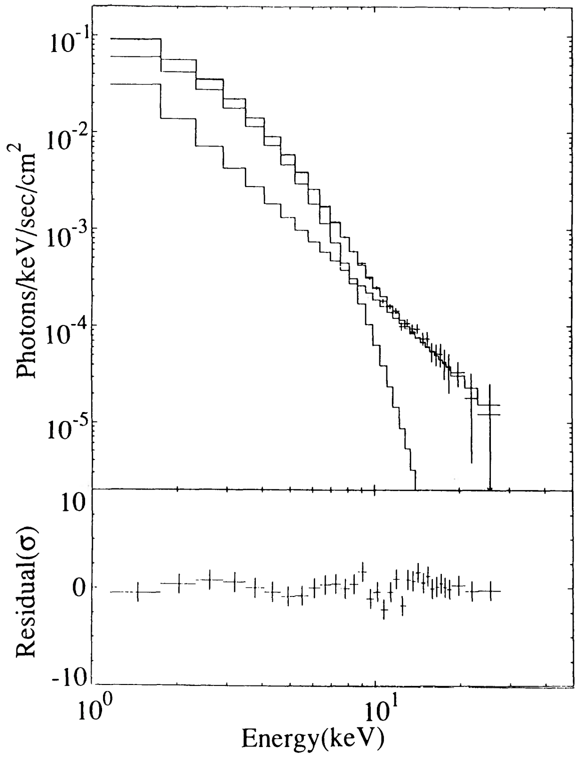

FIG. 3.—The incident photon spectrum (*crosses*) from LMC X-3 deconvolved using DBB + power-law model. The power law, DBB, and their sums are shown with histograms. The lower panel is the residuals of the fitting.

reduced combined spectra are reported in Figure 5. No lines are apparent above the continuum, which is well fitted by a reddened power ($\alpha_\lambda = 1.4$, $A_V = 0.28$). The observed state is fainter by a factor $\simeq 2$ with respect to that of 1987 January, when N v λ1240, Si IV λ1400, and C IV λ1550 resonance lines were also apparent (see Treves *et al.* 1988*a*). The brightness

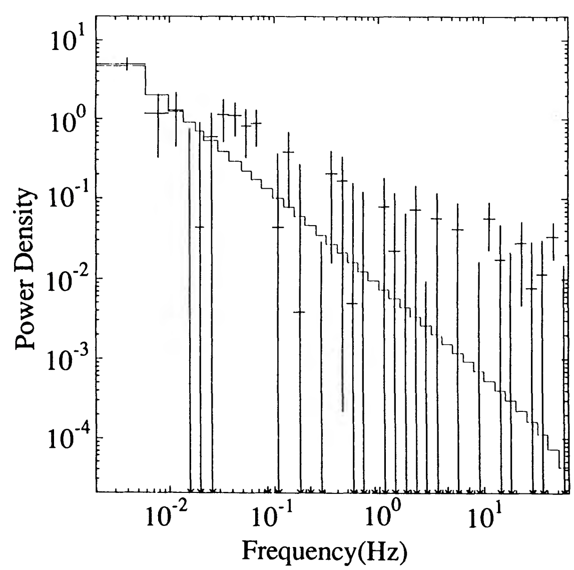

FIG. 4.—The power spectrum of X-rays from LMC X-3 in the energy range 1.2–37 keV (*crosses*). The white noise has been subtracted. The spectrum is an average of 32 power spectra, each obtained every 256 s of the MPC-3 mode data. The histogram is the best-fit power-law spectrum of index -1.1.

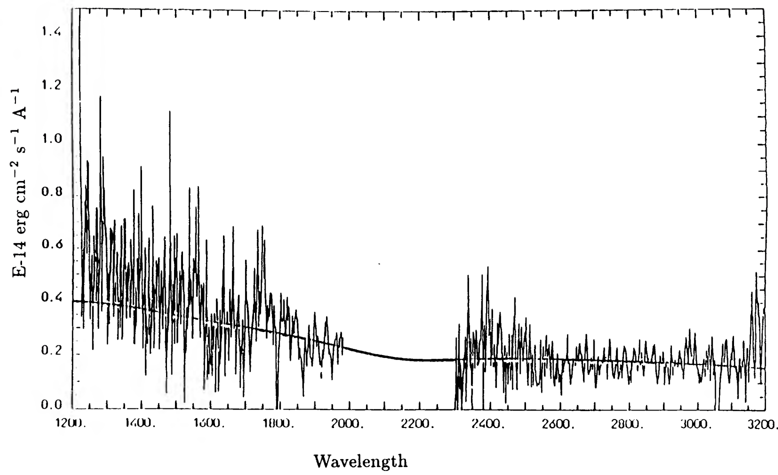

FIG. 5.—*IUE* spectrum of LMC X-3 observed on 1988 January. The continuum line represents a reddened power law (see text).

state is close to that of 1986 March, which was interpreted by Treves *et al.* (1988*a*) as being dominated by the optical star, with no, or little, contribution from the disk.

c) Optical Observations

Optical spectrophotometry of LMC X-3 was obtained during three nights at the ESO 1.5 m telescope at La Silla (see Table 1 and Fig. 6). We used a high-resolution CCD detector (RCA SID 503; 15 μm pixels) attached to a Boller & Chivens spectrograph. A 300 grooves mm^{-1} grating allowed the spectral range 4100–7300 Å to be covered in a single CCD frame with spectral resolution of 15 Å (FWHM). Several spectrophotometric standard stars (Stone 1977) were repeatedly observed during each night in order to calibrate the instrumental response. Comparison of different standard stars shows that the flux calibration was always better than 5% (2% on January 8; 5% on January 10 and 11). LMC X-3 was barely visible in the TV screen of the intensified guiding camera, and the centering of the object into the 8″ slit was established using many reference stars in the field. We estimate that, with the observed seeing of about 2″, the losses due to nonoptimal slit centering are <10%.

B and *V* magnitudes (see Table 1) were derived from monochromatic fluxes using the absolute calibration of Bessel (1979). The statistical errors of the monochromatic fluxes (rms of the mean) are lower than 3%. We assume, as a conservative error for the magnitudes reported in Table 1, 10% and 15%, respectively, for the observations of January 8 and January 10 and 11.

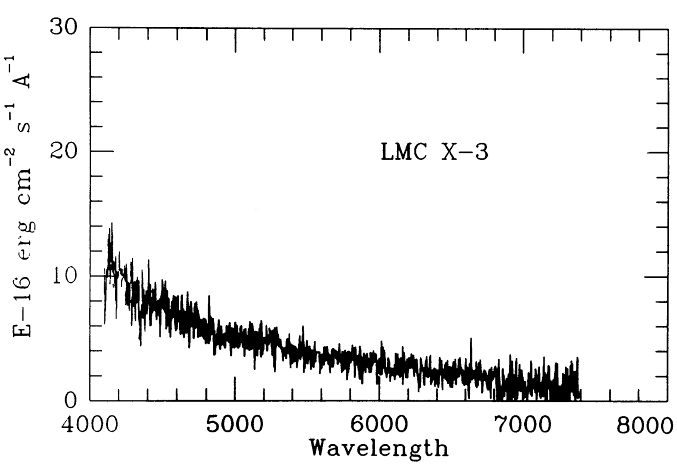

FIG. 6.—Spectrophotometry of LMC X-3 for 1988 January 10

Comparing the photometry of Cowley *et al.* (1984), van der Klis, Tjempkes, and van Paradijs (1983), van der Klis *et al.* (1985) and van Paradijs *et al.* (1987), one finds that the source was in a low state, possibly the lowest ever detected.

III. DISCUSSION

a) The X-Ray Energy Distribution

As shown in § II (see, in particular, Table 2), the X-ray energy distribution obtained with *Ginga* is well accounted for by two components, one which dominates at lower energies and which we will call thermal, and a high-energy tail. The thermal component is equally well fitted by a Comptonization model, or a DBB model.

The two component spectrum (thermal + power law) is widely observed in black hole candidates. Cyg X-1 exhibits bimodal spectral changes, and in the low state, it emits a power law with cutoff at about 100 keV (e.g., Steinle *et al.* 1982), while the high state is characterized by a steep spectrum below 8 keV and a hard tail (Tananbaum *et al.* 1972; Chiappetti *et al.* 1981). GX 339-4 undergoes also bimodal transitions, and a two-component spectrum was observed in the high state (Maejima *et al.* 1984; Makishima *et al.* 1986). Similar spectra were observed from LMC X-1 (Ebisawa *et al.* 1989).

From the viewpoint of bimodal behavior, LMC X-3 and LMC X-1 have been observed thus far only in the "high state," in contrast with Cyg X-1, which spends most of the time in the "low state."

On the basis of *EXOSAT* data (0.3–9 keV) Treves *et al.* (1988*c*) proposed an interpretation of the soft component of the spectrum of LMC X-3 in terms of the Comptonization model of Sunyaev and Titarchuk (1980), which was previously successfully applied to the low state of Cyg X-1 (Sunyaev and Truemper 1979). Although the soft component is indeed well represented by the Comptonization model (see Table 2), there are some difficulties in accepting the model. In fact the Sunyaev and Titarchuk picture requires that the seed photons are at an energy much lower than kT, while the low temperature and high optical depth constrain severely the temperature at which the plasma becomes transparent (see Treves *et al.* 1988*c*).

Moreover, because of the relatively low temperature, the vertical component of the gravitational field should yield a rather thin disk configuration, which differs significantly from the spherical one considered by Sunyaev and Titarchuk (1980).

On the other hand, DBB is a physically clear model. It describes the flux distribution from the optically thick disk regions, as superposition of blackbody rings of various temperatures depending on the radius. This of course requires that the optical depth perpendicular to the disk be large. The basic parameters are the inner disk radius and its temperature. The model was discussed by Hayakawa (1981), Hoshi (1984), Mitsuda *et al.* (1984) and Makishima *et al.* (1986). Good fits of the thermal component were obtained for low-mass X-ray binaries (Mitsuda *et al.* 1984), and for the black hole candidate GX 339-4 (Makishima *et al.* 1986). The thermal radiation of 1 keV observed in LMC X-3 is interpreted as being emitted from the inner accretion disk, and we refer to Makishima *et al.* (1986) for some further discussion on the case that the disk surrounds a black hole.

The origin of the hard tail from black hole X-ray sources is more difficult to interpret. Makishima *et al.* (1986) in the case of GX 339-4 proposed upscattering of the soft X-rays by an inner high-temperature transparent plasma of about 60 keV, a mechanism which could work also for LMC X-3. However, some correlation between the disk emission and the intensity of the hard tail is expected in this model. The spectra of the ultrasoft transient X-ray sources A0620−00 (Ricketts *et al.* 1985) and 4U 1630−47 (Parmar, Stella, and White 1986) exhibited spectral hardening with decreasing flux. On the other hand, uncorrelated spectral variations between the soft and hard components were observed from LMC X-1 (Ebisawa *et al.* 1989) and GS 2000+25 (Tanaka 1989). The correlation between the two components in LMC X-3 has not been explored thus far.

b) *X-Ray–Optical Correlation*

A second relevant result of our observations derives from he comparison with simultaneous optical and X-ray observations of 1984 December 15, when the source magnitude was $V = 17.0$ (see van Paradijs *et al.* 1978). While in the optical range the 1988 January state is lower by 50% with respect to 1984 December 15, in the 2–8 keV region where a direct comparison between *EXOSAT* and *Ginga* results is possible, the flux F(2–8 keV) $\simeq 3.2 \times 10^{-2}$ keV cm^{-2} s^{-1} has decreased by only 6%. It seems therefore that the optical flux does not respond proportionally to the X-ray illumination of the disk. Note, however, that the *Ginga* spectrum yields little information below about 1 keV, where most of the X-ray flux measured by *EXOSAT* resides; therefore, one cannot completely exclude the possibility that the X-ray heating of the disk was different at the two epochs.

If one assumes that the X-ray luminosities were very close at the two epochs, in order to explain the differences in the optical fluxes, a change in the disk structure or aspect can be considered. A simple picture would be a change in the disk thickness, or a modification of the surrounding corona. Note that the disk structure appears essentially stable on time scales of weeks, as manifested by the optical X-ray correlations detected in 1984 December (van Paradijs *et al.* 1987), but it could be unstable on time scales of years. A change of disk structure was also invoked by Corbet *et al.* (1989) to explain their simultaneous optical/X-ray observations of X1735−444 which would otherwise require an unreasonably low disk temperature.

A change in the disk aspect could suggest the presence of a precession phenomenon, which is invoked in a number of X-ray binaries and in particular in the two black hole candidates SS 433 and Cyg X-1. However, up to now, neither optical nor X-ray observations yield indication of a periodicity of weeks or months which would be the signature of the precession process.

An alternative scenario for explaining the variation of optical–to–X-ray ratio is to consider a change of the degree of isotropy of the X-ray emission at the disk's inner edge. The isotropy issue is rather uncertain, and in the models of interpretation of optical and UV photometry two possibilities have been considered, that the emission is isotropic $dL/d\Omega = L^{\rm tot}/4\pi$, or that it is planar, $dL/d\Omega = L^{\rm tot} \cos \vartheta/2\pi$, with possibly some corrections due to limb-darkening (Treves *et al.* 1988*b*; Bochkarev *et al.* 1988; Kuiper, van Paradijs, and van der Klis 1988). Obviously the disk heating is much less effective in the second case. If a transition between the two situations occurs, as explicitly considered for the case of LMC X-3 by Bochkarev *et al.* (1988) on the basis of instabilities discussed by Shakura and Sunyaev (1975), one can easily account for a drastic change in the optical flux, without a substantial variation of the X-ray one. Since the transition should affect mainly the inner disk, one would expect a clearer correlation of the optical with the hard X-rays, rather than with the soft ones. This may represent a distinguishing feature of this scenario.

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