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THE ULTRAVIOLET-OPTICAL-INFRARED ENERGY DISTRIBUTION OF LMC X-3: OBSERVATION OF AN ACCRETION DISK AROUND A BLACK HOLE[1]

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ABSTRACT

LMC X-3 was observed quasi-simultaneously at UV (*IUE*), optical, and IR (ESO, La Silla) frequencies in 1987 January. The overall energy distribution exhibits a broad peak around 10^{15} Hz. The UV flux appears well in excess of that measured by us in 1986 March, which can be attributed to the noncollapsed star in the system. The excess emission can be interpreted in terms of an accretion disk surrounding the collapsed component. A good spectral fit to the excess is obtained with a blackbody distribution with $T \approx 14{,}000$ K and a projected area $A \cos i \simeq 3.7 \times 10^{23}$ cm^2. Supposing that the disk radius equals the Roche lobe of the compact object, an inclination $i \simeq 55°$ is found. The results are discussed within the model of the system.

Subject headings: black holes — galaxies: Magellanic Clouds — stars: accretion — X-rays: binaries

I. INTRODUCTION

LMC X-3 is a bright X-ray source discovered with the *Uhuru* satellite (Leong *et al.* 1971) whose optical counterpart is a B V star (Warren and Penfold 1975). The X-ray intensity is variable by a factor ~ 100 (see Treves *et al.* 1988 and references therein). Cowley *et al.* (1983) found a spectroscopic period $P = 1.7$ days and a mass function $f = 2.3\ M_\odot$, which allowed them to make a strong case for a black hole component. In this regard see also Paczyński (1983) and the caveats by Mazeh *et al.* (1986).

The presence of an accretion disk around the collapsed object was inferred from the irregular variability in the optical photometry, which greatly exceeds the orbital modulation (van der Klis *et al.* 1985; van Paradijs *et al.* 1987). The quasi-simultaneous optical-UV-IR observations presented here are meant to contribute to the study of the accretion disk component. In fact, the case of LMC X-3 is nearly unique, allowing the observation of a disk around a stellar mass black hole over a relatively wide spectral range (1200–22,000 Å). In Cyg X-1 the optical star is so bright that it outshines the disk, while the star in A0602−00 is too faint (at least in the quiescent state) to be observed in the UV. For SS 433 the UV observations are precluded by heavy extinction.

Preliminary accounts of some of the results described here were presented at conferences (Treves *et al.* 1986, 1987).

II. OBSERVATIONS

LMC X-3 was observed in the 1200–3200 Å band with *IUE* in 1986 March and in 1987 January. At the latter epoch coordinated observations in the optical and IR bands were made at the European Southern Observatory at La Silla, Chile. A journal of the observations is reported in Table 1.

The *IUE* spectra were processed using the IHAP package developed at ESO. Regions affected by particle events and major flaws were recognized on the line-by-line extracted spectrum. In particular, this led to the exclusion of the region between 1480 and 1640 Å for the 1986 spectrum (SWP 27872). The 1986 and 1987 far-UV spectra are reported in Figure 1, where a large variation between the two epochs is apparent. In the 1987 spectrum weak emission features attributable to N V λ1240, Si IV λ1400, and C IV λ1550 are visible with equivalent widths ~ 17, ~ 10, and ~ 8 Å, respectively.

Two spectra were obtained in the optical region (3800–8400 Å) on 1987 January 9 and 11 at the ESO 1.5 m telescope equipped with the Boller & Chivens spectrograph and Image Dissector Scanner (IDS) at a resolution of 18 Å (FWHM). The data were reduced using the standard procedure, including photometric calibration derived from the observation of several standard stars (Stone 1977). The photometric accuracy of the spectrum taken on January 11 is better than 10%, while for that of January 9 the accuracy is $\sim 30\%$. The January 11 spectrum, integrated over selected energy bands, is reported in Figure 2. The corresponding V-magnitude is ~ 16.7. Comparing with the photometry of van der Klis, Tjempkes, and van Paradijs (1983) and van der Klis *et al.* (1985) and van Paradijs *et al.* (1987), which gives $17.5 \le V \le 16.8$ mag, one recognizes that a high state of the source was observed.

Near-infrared broad-band photometry in the filters J ($\lambda_{\rm eff} = 1.24\ \mu$m), H ($\lambda_{\rm eff} = 1.63\ \mu$m), and K ($\lambda_{\rm eff} = 2.18\ \mu$m) was obtained on 1987 January 9, simultaneously with the optical data, at the ESO 3.6 m telescope equipped with the InSb photometer. The magnitudes recorded in the photometric system in use at the ESO were $J = 16.9 \pm 0.2$, $H = 17.1 \pm 0.3$, $K = 16.4 \pm 0.3$. Conversion to flux density has been performed using the following zero-magnitude values: $J = 3.24 \times 10^{-10}$, $H = 1.26 \times 10^{-10}$, $K = 4.2 \times 10^{-11}$ (ergs cm^{-2} s^{-1} Å^{-1}).

III. THE ENERGY DISTRIBUTION OF THE B STAR

The fluxes at the two epochs integrated over convenient intervals are reported in Figure 1. The lowest state UV data of 1986 March are represented by diamonds. B and V fluxes corresponding to the lowest state of the sources, from the photometry of van Paradijs *et al.* (1987), are also reported.

In order to estimate the continuum of the B star, we assume that the low-state fluxes can be described by a reddened Kurucz model (Kurucz 1979) of spectral class B3 V with

[1] Based on UV observations with the *International Ultraviolet Explorer* collected at the European Space Agency station in Madrid. Optical and IR observations were obtained at the European Southern Observatory, La Silla, Chile.

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TABLE 1

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Instrument	Spectral Range (Å)	Spectrum Identifier	Observation Date (UT)	Observation Phase	Exposure (minutes)	Flux (ergs cm^{-2} s^{-1} Å^{-1})
IUE	2000–3200	LWP 7753	1986 Mar 7 04:15	0.85	385	$F_{2550} = 1.6 \times 10^{-15}$
IUE	1700–1950	SWP 27872	1986 Mar 8 05:56	0.47	281	$F_{1740} = 3.94 \times 10^{-15}$
IUE	1200–1950	SWP 30059	1987 Jan 9 08:09	0.61	395	$F_{1740} = 6.50 \times 10^{-15}$
IUE	2000–3200	LWP 9942	1987 Jan 16 07:42	0.71	183	$F_{2550} = 3.37 \times 10^{-15}$
1.5 m ESO BC + IDS[a]	3850–8250	...	1987 Jan 11 04:00	0.69	48	$F_{5500} = 8.20 \times 10^{-16}$
3.6 m ESO + InSb	...	...	1987 Jan 8 03:40	0.92	...	$F_{(J)} = 5.6 \times 10^{-17}$ [b] $F_{(H)} = 1.8 \times 10^{-17}$ $F_{(K)} = 1.2 \times 10^{-17}$

a Boller & Chivens spectrograph with Image Dissector Scanner.
b See text.

$T_{star} \sim 19{,}000$ K (Cowley *et al.* 1983). The other parameters entering in the Kurucz model are the radius and surface gravity of the star. For the radius the Popper (1980) formula is used:

$$\log \frac{R}{R_\odot} = 7.45 - 2F_v - 0.2m_v + 0.2A_V + \log d\ , \qquad (1)$$

where $F_v = 4.086$ for a B3 V star and the distance d is 55 kpc. For log g we take ~ 3.7. The only remaining relevant parameter is the extinction. The extinction corresponding to the Galactic hydrogen density derived from 21 cm measurements is $A_V^{Gal} \sim 0.2$. However, normalizing at the V-magnitude, the UV fluxes computed from the Kurucz model, and reddened with $A_V^{Gal} = 0.2$, are higher than those observed by us in the low state. An interpretation which seems reasonable is that the extinction exceeds the Galactic one, with a contribution from the LMC. We have therefore fitted the UV and V, B low-state fluxes with a Kurucz model at 19,000 K, a radius from formula (1), and a reddening $A_V = A_V^{Gal} + A_V^{LMC}$, with $A_V^{Gal} = 0.2$ and A_V^{LMC} as a free parameter. The adopted extinction curves for the Galaxy and the LMC are from Seaton (1979) and Fitzpatrick (1986), respectively. At the 90% confidence level $A_V^{LMC} = 0.08 \pm 0.01$. This is consistent with the hydrogen column density deduced from X-ray observations (Treves *et al.* 1988).

In Figure 2 the reddened Kurucz model is reported. This model appears to account satisfactorily for the optical to UV

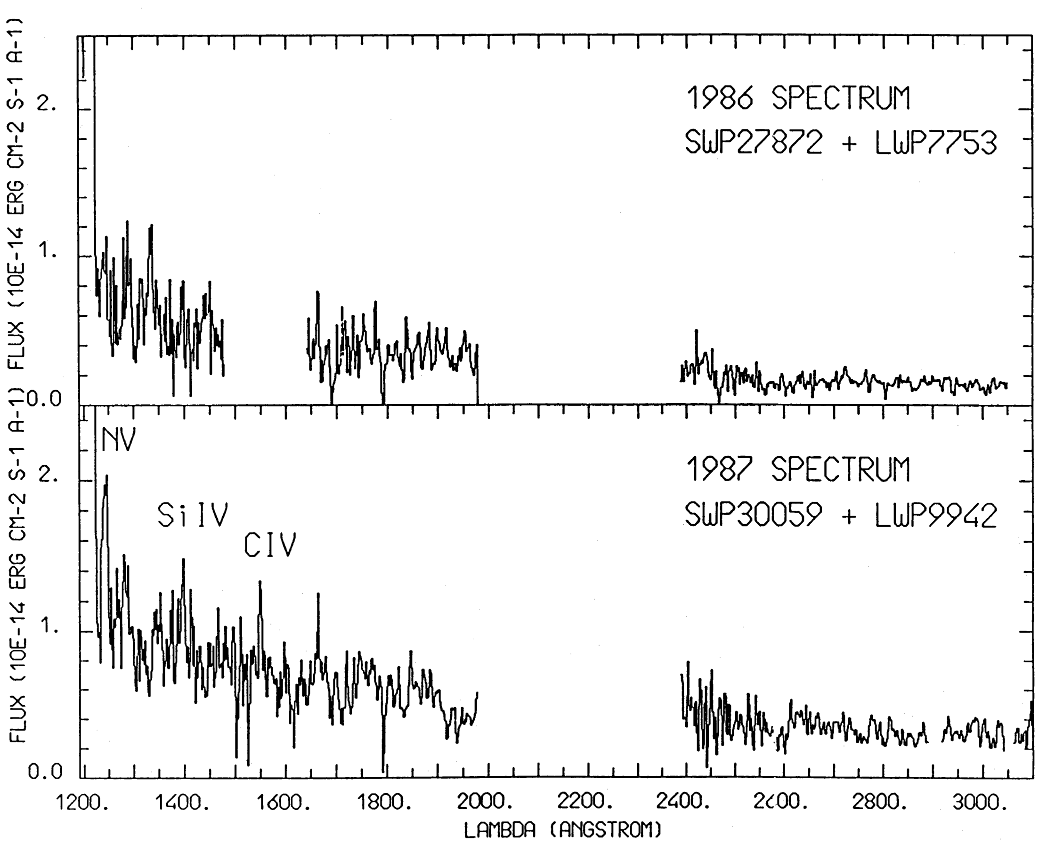

FIG. 1.—*IUE* spectra of LMC X-3: in low (*upper frame*; 1986 March 6) and high (*lower frame*; 1987 January 9) state

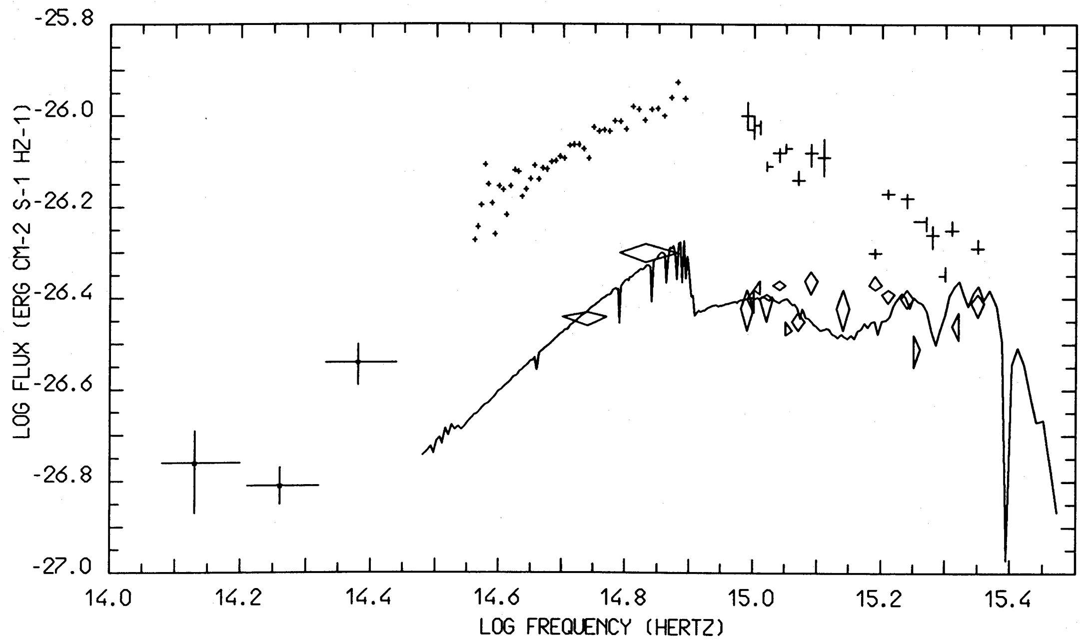

FIG. 2.—IR to UV energy distribution of LMC X-3. Crosses correspond to observations of 1987 January, diamonds (UV) to 1986 March. Fluxes in the V and B bands correspond to the lowest state of the source. The continuum tracing represents the Kurucz model of a reddened B3-V star (see text).

distribution in the low state as due solely to the optical star. Therefore, even if some contribution from the disk is present in the low state, it seems that it can be neglected with respect to that of the star.

IV. THE DISK ENERGY DISTRIBUTION

In order to derive the energy distribution of the disk, we have subtracted the Kurucz model specified above from the fluxes measured during the high state of 1987 January. The result is given in Figure 3. The spectrum is weakly increasing in the optical, has a maximum between 3600 and 3000 Å, and steepens in the UV. This shape clearly suggests blackbody energy distribution. The fit of the data with a blackbody distribution reddened as discussed above yields $T_{\rm disk} = 14{,}590 \pm 220$ K and $A \cos i = (3.7 \pm 0.2) \times 10^{23}$ cm^2 (90% confidence). The temperature and area of the disk depend, though weakly, on the continuum with which the spectrum of the star is fitted. We have repeated the procedure described above, assuming a range for the temperature of the Kurucz model: $T = 18{,}000$ and 20,000 K. This yields $T_{\rm disk} = 15{,}400$ and 13,300 K and projected areas $A \cos i = 3.3 \times 10^{23}$ and 4.6×10^{23} cm^2, respectively.

V. DISCUSSION

The temperature of the disk derived above is appreciably lower than that of the normal star, contrary to the usual situation for low-mass X-ray binaries and cataclysmic variables. This is consistent with the observation by van Paradijs *et al.* (1987) that the source is redder when it is brighter, since it is the redder component (the disk) which is variable.

The bolometric luminosity of the disk, as from the parameters given above, is $L_{\rm bol} \sim 3 \times 10^{36}$ ergs s^{-1}, about 1% of the X-ray luminosity (0.1–9 keV) measured in 1983–1984 (Treves *et al.* 1988). This is too high to be the intrinsic emission from the outer regions of the disk. The most plausible interpretation is that the disk intercepts and reprocesses $\sim$1% of the X-ray luminosity originating close to the central black hole. The blackbody distribution, with which we have fitted the disk emission, may be considered an approximation of the reprocessed emission. A strong argument in favor of this hypothesis is the correlation between the optical and the X-ray flux found by van Paradijs *et al.* (1987). Unfortunately, those simultaneous observations do not cover a wide intensity range. The required width h/r for the outer part of the disk is $\sim 10^{-2}$ or larger if the X-ray emission is anisotropic. A width $h/r \sim 10^{-2}$ is close to the value expected from standard disk models (e.g., Shakura and Sunyaev 1973). On the other hand, as noted by Shakura and Sunyaev, under conditions of strong X-ray irradiation the geometrical thickness of the disk could increase and a wind or corona should result, consistent with the indication of the presence of UV emission lines. A thickening of the disk structure is also required in order to justify the absence of a substantial heating of the noncollapsed star, as indicated by the shape of the optical light curve (van der Klis *et al.* 1985).

The projected area of the disk may be used to estimate the inclination angle, which is one of the unknown parameters in the system. We start from the usual assumption that the disk radius equals the Roche lobe of the collapsed object. This is given by (Paczyński 1980)

$$R_X = \frac{K_B P}{2\pi} g(q) \frac{1}{\sin i}, \quad (2)$$

where $K_B = 235$ km s^{-1} is the radial velocity of the B star as given by Cowley *et al.* (1983), $q = M_B/M_X$ is the mass ratio, and

$$g(q) = (1 + q)(0.38 - 0.2 \log q) . \quad (3)$$

Following van Paradijs *et al.* (1987), we take for $g(q)$ its mean value $\bar{g} = 0.68$, since, for the range $q = 0.05$–1, $g(q)$ varies only by 20%. This yields

$$\frac{R_X}{R_\odot} = \frac{5.4}{\sin i} . \quad (4)$$

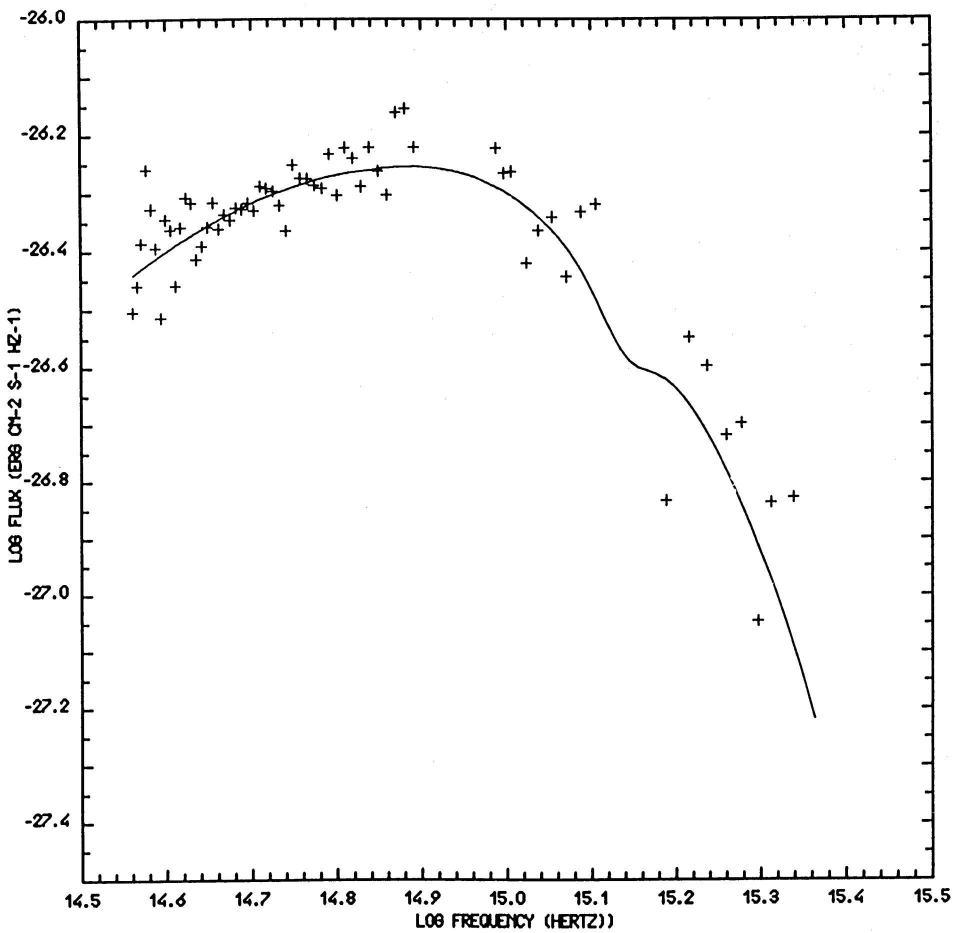

FIG. 3.—Difference between the 1987 January high-state energy distribution and the Kurucz model representing the visible component. The continuous curve is a reddened blackbody distribution fitted to the data.

We can then equate the projected area of the disk and the Roche lobe area,

$$\pi R_X^2 \cos i = A \cos i , \quad (5)$$

and, inserting equation (4) and the value of $A \cos i$ given in the previous section, we obtain $i \sim 55°$ (for $T_{\rm star} = 18{,}000$ K and $T_{\rm star} = 20{,}000$ K we find $i \sim 58°$ and $i \sim 51°$, respectively). Since

$$M_X = \frac{(1+q)^2}{\sin^3 i} f(M) , \quad (6)$$

we immediately find $M_X > 4\ M_\odot$, independent of the mass ratio. Even assuming that K_B is 0.8 times the value given by Cowley *et al.* (1983) and $M_B \sim 0.7\ M_\odot$, as proposed in an extreme example by Mazeh *et al.* (1986), M_X turns out to be larger than 3 $M_\odot$.

VI. CONCLUSION

Simultaneous optical and UV observations allowed us to deconvolve the energy distribution of the accretion disk in LMC X-3. The bulk of the disk emission is due to X-ray radiation reprocessed in the outer parts. Attributing the size of the Roche lobe to the reprocessing region, an inclination angle is found, $i \sim 50°$–$60°$, from which a lower limit $M_X \geq 3\ M_\odot$ for the collapsed object is inferred. A further study of X-ray reprocessing in the disk clearly requires simultaneous optical–UV–X-ray observations.

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