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UBV photometry of the optical candidate for LMC X-3*

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Summary. Results are reported of two weeks of optical photometry of the optical counterpart of LMC X-3 obtained in December 1981. When folded modulo the 1.7 d period recently proposed for this system on the basis of radial velocity measurements, the data show a brightness minimum near the inferior conjunction of the X-ray source. Combining our data with photometry obtained in 1974, we find long-term brightness variations over a range of up to 0.5 mag. Removing these, we find a double-wave orbital light curve with an amplitude of ~0.2 mag. We determine a mean period for the interval 1974–1981 of 1.70502±0.00005 d. We show that the observed light curve may be dominated by ellipsoidal variations, and that an additional light source, presumably an accretion disk, is likely to be present in the system.

Key words: LMC X-3 – X-ray binaries – variable stars

I. Introduction

LMC X-3 was first reported as an individual point-like X-ray source located in the Large Magellanic Cloud by Leong et al. (1971). After a reduction of the area of the error region by observations with the Copernicus satellite (Rapley and Tuohy, 1974), a faint OB star was first pinpointed as a promising optical candidate for the source by Warren and Penfold (1975). This identification was strengthened by improved-accuracy determinations of the position of LMC X-3 (Delvaille et al., 1976; Johnston et al., 1978; Long et al., 1981) and by the observed variability (Warren and Penfold, 1975; Cowley et al., 1978), UV-excess and weak Hβ-emission (Cowley et al., 1978) of the optical star. The large radial velocity of the star confirmed its membership of the LMC (Johnston et al., 1978). The system has a large X-ray to optical luminosity ratio, ~140 (Bradt and McClintock, 1983).

Very recently, Cowley et al. (1983) determined a radial velocity curve of this star which has an amplitude of ~235 km s^{-1} and a period of ~1.7 d. They classify the star as B3V, and on this basis determine a mass of ~9 $M_{\odot}$ for the compact object, implying that it is a black hole.

In this paper, we present optical photometry of this star performed in December 1981 and compare our results to photometric data given by Cowley et al. (1983) which were obtained in 1974.

* Based on observations at the European Southern Observatory

Table 1. Photometry of the optical counterpart of LMC X-3

Date (Dec. 1981) =JD−2444938.5	B	$U-B$	$B-V$
6.31	17.32	−0.68	−0.05
7.24	17.11	−0.52	−0.14
8.22	17.07	−0.48	−0.02
8.34	17.19	−0.66	−0.18
13.07	17.30	−0.60	−0.25
14.08	17.31	−0.61	−0.21
15.08	17.16	−0.63	−0.25
15.25	17.17	−0.61	−0.18
16.09	17.20	−0.65	−0.20
16.22	17.22	−0.78	−0.14
18.09	17.34	−0.71	−0.26
Average	17.22	−0.63	−0.17
Standard deviation	± 0.09	±0.08	±0.08

II. Observations

The optical counterpart of LMC X-3 was observed between December 6 and 18, 1981 with a two-channel photometer attached to the Danish 1.5 m telescope at ESO (La Silla). This photometer allows to measure star and night sky simultaneously. We used 9″ diaphragms and standard Johnson *UBV* filters together with EMI 9798 QA photomultipliers in both channels during all observations. The relative sensitivity of the two channels was determined by frequent measurements of bright stars through both channels of the photometer. As comparison stars we used blue supergiants in the LMC selected from the list of Dachs (1972) (stars 1–19, 1–24, 2–5 and 2–8). The sky brightness was measured at a fixed position approximately 62″ South with respect to the star. Although this position is close to that of star 32 (Cowley et al., 1978), no contaminating starlight was visible through the sky diaphragm using the integrating TV system attached to the telescope. Comparison to sky measurements at nearby positions in the LMC showed that sky contamination could not have contributed more than 0.04 mag to the observed *B*-magnitude of the optical counterpart of LMC X-3, and could have changed the measured colours by +0.02 $(U-B)$ and −0.03 mag $(B-V)$ at most.

The results of the photometry are listed in Table 1. Full moon occurred on December 12, and no reliable measurements could be made during this night and the nights immediately before and

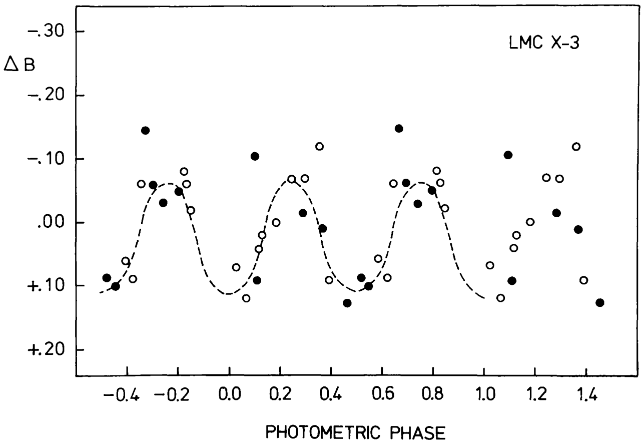

Fig. 1. The photometric variability of the optical counterpart of LMC X-3 plotted against photometric phase (phase zero = X-ray source superior conjunction). Data obtained in 1974–1975 (Cowley et al., 1983, open circles), and in December 1981 (this paper, filled circles) were reduced to the same magnitude range by subtracting an average magnitude from each of four groups of points taken closely together in time. The dashed curve is hand-drawn, and is intended solely as a guide to the eye

Table 2. Long-term photometric variations of the optical counterpart of LMC X-3

Interval	Number of observations	Mean of observed B-values	Ref.
Nov. 13–17, 1974	5	16.82	Cowley et al. (1983)
Dec. 19–22, 1974	5	16.66	Cowley et al. (1983)
Jan. 08–14, 1975	5	16.87	Cowley et al. (1983)
Dec. 06–18, 1981	11	17.22	This work

after, except on one occasion (December 13), when the moon was near the horizon. The accuracy of the B-magnitudes varies between 0.02 and 0.05 mag, which includes counting statistics, fluctuations in the relative sensitivity of the two photometer channels and uncertainties in the magnitudes of the comparison stars. The standard deviation of the B-values, 0.09 mag, is significantly larger than this, confirming the variability of the star.

Correlated variability occurs in the two other bands, but the accuracies of the U and V magnitudes (estimated in the same way as for B), are 0.03–0.08 and 0.05–0.15 mag, respectively, and do not allow the detection of colour variations. The mean value of $U-B$ obtained here (see Table 1) is consistent with the value quoted by Warren and Penfold (1975), but $B-V$ appears to have decreased. The star was significantly weaker during our observations than when these authors observed it, by $\Delta B \sim 0.4$ mag.

III. Analysis

To look for possible photometric variability with the period found in the radial velocity of the star by Cowley et al. (1983), we folded our data modulo the 1.70491 d period given by these authors. Phase zero was chosen to correspond to JD 2445278.02, which is the expected time of superior conjunction of the X-ray source assuming a circular orbit ("photometric phase").

In the resulting phase diagram (see Fig. 1; our data are indicated by filled circles, the mean value of B was subtracted from the data prior to plotting) a minimum appears near phase 0.5. The depth of the minimum, as defined by the brightness difference between phase 0.75 and phase 0.50, is ~ 0.2 mag. Near phase 0.0 the phase coverage is insufficient and the scatter of the data points too large, to draw conclusions on the light curve on the basis of our data alone.

We have supplemented our data with the results of photometric measurements given by Cowley et al. (1983). These authors list three groups of photometric measurements, which were obtained with intervals of several weeks. Each group contains 5 measurements, taken in most cases in consecutive nights. The mean values of the B-magnitudes of the three groups span a range of 0.2 mag, and differ by 0.3 to 0.5 mag from our mean value of B. The distribution of the points in each group over the 1.7 d cycle justifies the assumption that these differences in the mean B-magnitude are not caused by photometric variations with the 1.7 d period. We removed these differences by subtracting in each group the mean B-magnitude from the individual points. The subtracted values are tabulated in Table 2. After folding modulo the 1.7 d period, the ΔB values thus obtained also show evidence for a double-wave phase related variation, shifted in phase, however, by 0.10 ± 0.04 with respect to our measurements. These points were taken in 1974, seven years before ours. Consequently, this phase shift corresponds to a correction to the binary period of $+0.00011 \pm 0.00005$ d, which is reasonable in the light of the 0.00007 d error quoted for this period by Cowley et al. (1983). We therefore conclude to a mean binary period between 1974 and 1981 of 1.70502 ± 0.00005 d.

The data of Cowley et al. (1983) were also plotted in Fig. 1 (open circles) with the above-mentioned phase-shift applied. Together, the two data-sets define a double-wave light curve with two approximately equal maxima, and approximately equal minima. The amplitude of the modulation is 0.18 ± 0.03 mag.

IV. Discussion

The above results suggest, that the observed variability of the optical counterpart of LMC X-3 consists of two components: long-term brightness changes (over a range of at least ~ 0.4 mag) and a variation with the 1.7 d period. The double-wave character of the latter, and the occurrence of the minima at the times of the conjunctions of the two components of the system, indicate that ellipsoidal variability, due to the aspect changes of a tidally distorted primary star, may dominate the orbital light curve.

a) *Long-term brightness changes*

The long-term brightness variation could be due to intrinsic variability of the primary star, or be related to the presence of a strong X-ray source.

Although no evidence is available that the primary has a Be-character, we wish to direct attention to the possible relation of the observed long-term variability with the type of variations observed in Be-stars, in particular since most of the non-evolved primaries of massive X-ray binaries are known to show Be-characteristics (Rappaport and van den Heuvel, 1982). Brightness variations in excess of ~ 0.5 mag have been observed in a number of well-studied Be-stars (Dachs, 1982). Furthermore, in many cases changes in brightness and colour indices have been found to be correlated. For the differences of the average values of V, $B-V$ and $U-B$ between our data and the data presented by Cowley et al. (1983) we find $\Delta V/\Delta(B-V)=-4.5$ and $\Delta(U-B)/\Delta(B-V)=-0.3$. These ratios fit well within observed Be-star variability (Hirata, 1982).

Optical brightness variations related to the presence of a strong, variable X-ray source in the system can be produced by heating of the side of the primary which is facing the X-ray source. However, if this heating is the cause of the observed long-term brightness variations, one would expect that during an optically bright state the minimum at phase 0.5 would disappear completely. This points to an accretion disk as a more likely site of additional optical emission, similar to what has been inferred from the light curves of the systems SMC X-1 (van Paradijs and Zuiderwijk, 1977), LMC X-4 (Chevalier et al., 1981, 1983) and Cen X-3 (van Paradijs et al., 1983). The absolute magnitudes of the accretion disks in these systems are $M_V \sim -2$. If such a disk were present intermittently in LMC X-3, variations of ~ 0.4 mag in the total brightness of the system would seem to be quite possible.

This hypothesis has the advantage that it may explain the absence of a Her X-1 heating-type light curve. The strong heating which would be expected from the high observed ratio of X-ray to optical luminosity (among the highest observed for massive X-ray binaries), would be avoided by shielding of the primary star from the X-rays by the disk. Such shielding has been proposed in the case of SMC X-1 in order to explain the shape of the light curve of that system (Avni and Milgrom, 1977; van Paradijs and Zuiderwijk, 1977), and also is a generally accepted feature in models of low-mass X-ray binaries (Milgrom, 1978; Lewin and Joss, 1983).

We wish to point out the existence of a possible problem in explaining the long-term variability of LMC X-3 by the variable contribution of an accretion disk, which is, that one would expect ellipsoidal variations to have a $\sim 40\%$ smaller relative amplitude when the total system brightness is up by that amount. Our data do not seem to support such a change in amplitude. Several effects which could influence the amplitude of the observed light curve are discussed below. We mention here, that the problem does not arise if the long-term variability is intrinsic to the primary star, and that it could possibly also be solved by assuming that partial disk eclipses do occur in the system. Of course, one cannot exclude the possibility that several effects contribute to the brightness changes.

b) Orbital brightness variations

We now turn our attention to the orbital brightness variations. A possible problem we have to face in interpreting the observed double-wave light curve as ellipsoidal variations is that – even though phase coverage around phase zero is rather too sparse to allow an accurate determination of the depth of this minimum – the data suggest that the two minima in the light curve are approximately equal. In an ellipsoidal light curve the minimum at phase 0.5 is deeper by ~ 0.05 mag because of the lower value of surface gravity and effective temperature in the direction of the inner Lagrangian point. There are various possibilities to explain this discrepancy.

In the first place the minimum at phase 0.5 may be partially filled in by X-ray heating. As mentioned above, at the observed high ratio of X-ray to optical luminosity no minimum at all would

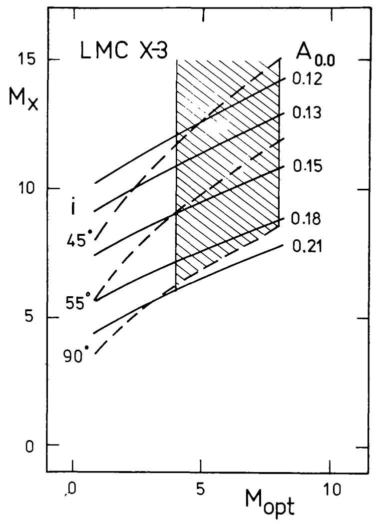

Fig. 2. The relation between the primary mass M_{opt} and the mass of the X-ray source M_x for different values of the depth $A_{0.0}$ of the minimum of the orbital light curve near phase 0.0, assuming a mass function of 2.3 $M_\odot$ (drawn curves). Dashed curves are lines of constant inclination as derived from the mass function

be expected if the X-rays could reach the primary without being intercepted by an accretion disk. Since the residual amount of heating depends on the thickness of the accretion disk (about which no direct information is available), and, furthermore, the total brightness of the system at phase 0.5 may be influenced by a possible fractional occultation of the primary by the disk, it is not possible at present to make a quantitative estimate of the extent to which the depth of the minimum at phase 0.5 could differ from the ellipsoidal value.

A second possible explanation for the discrepancy is that the minimum near phase 0.0 has deepened because of the fractional occultation of an accretion disk by the primary. We find that the fact that no deep eclipses are seen in the optical light curve when the system is bright, implies that the fraction of the disk occulted by the primary is less than $\sim 30\%$. This is consistent with the fact that, since no X-ray eclipses are observed from LMC X-3 (Cowley et al., 1983), the fraction of the disk that can be occulted by the primary is less than $\sim 25\%$ (assuming that both the primary and the disk fill their Roche lobes, and that the disk is in the plane of the orbit; this value is slightly dependent on the mass ratio of the system).

If fractional occulations of the disk by the primary occur, one would also expect the disk to occult the primary at phase 0.5, and unless the surface brightness of the disk is substantially higher than that of the primary, no large differential effect on the depth of the two minima would result.

We note that fractional occultations involving a fraction of $\sim 20\%$ of the disk would be sufficient to explain the apparently unchanged light-curve amplitude during the bright state discussed above. In this case changes in the shape of the orbital light curve would be expected, which would be correlated to the long-term brightness variations.

It is not possible on the basis of the presently available information to decide which of the mentioned effects is most important in establishing the equality of the depths of the two minima. However, it does follow from the above discussion that the depth of the minimum near phase 0.0 can reasonably be considered an upper limit to the value expected from ellipsoidal variations.

c) Ellipsoidal light curves

In order to study the consequence of this conclusion we have made some calculations of theoretical light curves, in which it was assumed that the primary star fills its Roche lobe. In view of the exploratory nature of these calculations we have furthermore made the assumption that the primary co-rotates with the orbital frequency, that Von Zeipels "theorem" is applicable for the calculation of the distribution of effective temperature and gravity across its surface, and – finally – that X-ray heating of the primary can be neglected. As parameters in our calculation we use the primary mass M_{opt}, its bolometric luminosity L_{bol}, the mass ratio $q=M_x/M_{opt}$ and the inclination i of the orbital plane.

For L_{bol} we took values between $4.0\,10^{36}$ and $1.2\,10^{37}\,\mathrm{erg\,s^{-1}}$, corresponding to bolometric magnitudes between -2.7 and -4.0 (Cowley et al., 1983). According to a few trial calculations the light curves depend only very little on the value of L_{bol}, and we subsequently used $L_{bol}=6\,10^{36}\,\mathrm{erg\,s^{-1}}$.

The mass function is known from the radial velocity curve obtained by Cowley et al. (1983):

$$f(M_{opt})=(M_x^3\sin^3 i)/(M_x+M_{opt})^2$$
$$=(M_{opt}q^3\sin^3 i)/(1+q)^2=2.3\,M_\odot\,.$$

By choosing a particular value for M_{opt} a unique relation between q and i is determined. The amplitude of the ellipsoidal light curve depends uniquely on M_{opt}, q and i. Consequently, for given M_{opt}, a particular value of the light-curve amplitude together with the mass function uniquely determines q (and i). Summarizing, if the mass function of the system is given, and we make the assumption that the primary fills its Roche lobe, the amplitude of the light curve defines a relation between M_x and M_{opt}.

The results of our calculations are shown in Fig. 2, where these relations between M_x and M_{opt} are given for several values of the lightcurve amplitude at phase 0.0, $A_{0.0}$ (drawn curves). Also shown in Fig. 2 are lines of constant i as derived from the mass function (dashed curves).

Clearly, the assumption, that our observed light curve is due to ellipsoidal variations of a Roche-lobe filling star, is consistent with the mass function derived by Cowley et al. (1983). It can further be seen, that if the minimum at phase 0.0 is indeed caused by ellipsoidal variations only, and if $M_{opt}>4\,M_\odot$ (Cowley et al., 1983), our observed value of $A_{0.0}$, 0.18 ± 0.03 mag, implies that $i\gtrsim55°$.

Further observations with good orbital phase coverage are necessary to gain a better understanding of the LMC X-3 system. A study of the shape of the minima of the orbital light curve could decide whether the photometric variations are purely ellipsoidal or whether partial occulations of an accretion disk are occurring. In addition to this, investigations of the correlation between the long-term brightness variations and possible changes in the 1.7 d light curve will make it possible to obtain information on the nature of both the long-term and the orbital variability.

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