



UvA-DARE (Digital Academic Repository)

Analysis of the optical light curve of LMC X-3

Kuiper, L.; van Paradijs, J.; van der Klis, M.B.M.

Published in:
Astronomy & Astrophysics

[Link to publication](#)

Citation for published version (APA):

Kuiper, L., van Paradijs, J., & van der Klis, M. (1988). Analysis of the optical light curve of LMC X-3. *Astronomy & Astrophysics*, 203(1), 79-84.

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <http://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Analysis of the optical light curve of LMC X-3

L. Kuiper^{1,*}, J. van Paradijs¹, and M. van der Klis²

¹ Astronomical Institute “Anton Pannekoek”, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands

² EXOSAT Observatory, Space Science Department of the European Space Agency, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

Received January 20, accepted March 11, 1988

Summary. We have analyzed the optical orbital light curve of the X-ray binary LMC X-3, using a model comprising ellipsoidal variations, X-ray heating of the companion star, and the effects of an accretion disk (as an additional source of optical emission, partial X-ray shielding of the companion, and possible mutual eclipses). Using observational constraints on the system (mass function, apparent visual magnitude and spectral type of the companion star) we find that the observed amplitudes of the optical light curve constrain the mass M_X of the compact star in LMC X-3 to be within the range $(4.5-6.5)(d/50 \text{ kpc}) M_\odot$. We have studied the effects of varying the mass function, the geometry of the X-ray emitting region, and the radius of the accretion disk, and find a lower limit on M_X (for a 2σ lower limit to the mass function of $1.7 M_\odot$, a source distance of 40 kpc, and a flat X-ray emitting region) of $2.8 M_\odot$. We conclude that within the framework of our model for the optical variations of LMC X-3 the compact star in this system is likely a black hole.

Key words: X-ray binaries – black holes

1. Introduction

Because of the large mass function ($2.3 \pm 0.3 M_\odot$; Cowley et al., 1983) derived from the radial-velocity curve of the optical counterpart (Warren and Penfold, 1975) of LMC X-3 (Leong et al., 1971) this X-ray source is one of only three known good candidates for a black hole with a mass in the stellar mass range (cf. Paczynski, 1983; Mazeh et al., 1986; for a recent review of the evidence for black holes see McClintock, 1987).

Periodic orbital variations ($P_{\text{orb}} = 1.70480 \text{ d}$, see Van der Klis et al. 1984) have been observed in the optical brightness of LMC X-3 (Van der Klis et al., 1983), but not in X rays (Cowley et al., 1983). On a time scale of weeks the X-ray flux changes substantially, but no periodicity has been detected in these variations (see Treves et al., 1988 for a compilation of the results of X-ray observations of LMC X-3). The optical brightness also shows a long-term irregular variation superposed on the orbital light curve, with an amplitude of $\sim 0.5 \text{ mag}$ (Warren and Penfold,

1975; Van der Klis et al., 1983; 1985; Van Paradijs et al., 1987). From contemporaneous X-ray and optical observations of LMC X-3 made in December 1984 it appears that this long-term component of the optical brightness variation is correlated with the long-term variation of the X-ray flux (Van Paradijs et al., 1987).

The optical light curve (after correction for the long-term trend) shows a double-wave variation, with two equal maxima, and two approximately equal minima. If it is assumed that the light curve is symmetric with respect to phases 0.0 and 0.5 (as in our models; see below) the depths of the minimum at phase 0.0 (superior conjunction of the X-ray source) and phase 0.5 are $A_{0.0} = 0.157 \pm 0.005 \text{ mag}$, and $A_{0.5} = 0.147 \pm 0.006 \text{ mag}$, respectively (Van Paradijs et al., 1987).

The correlated long-term optical and X-ray variations can be described in terms of a model comprising a constant secondary star ($V \sim 17.5$, and $B - V \sim -0.2$), and an accretion disk (average blackbody temperature $< 15,000 \text{ K}$) radiating through reprocessing of X-rays (Van Paradijs et al., 1987).

The double-wave optical light curve suggests that ellipsoidal variations, due to tidal and rotational distortion of the companion star, contribute significantly to the brightness variations of LMC X-3. In view of the large ratio of X-ray to optical luminosity of LMC X-3 ($F_X/F_{\text{opt}} \sim 50$ during the contemporaneous X-ray and optical observations in December 1984) one would expect that the minimum near phase 0.5 would be completely filled in due to heating of the companion star by X-rays. The near equality of the two minima in the light curve indicates that shielding of the companion star by a thick accretion disk is important (cf. Van der Klis et al., 1985).

Motivated by the hope to derive an (admittedly model dependent) constraint on the mass of the compact star in LMC X-3 we will in this paper attempt to give a more detailed description of the optical light curve of LMC X-3 in terms of a simple geometric model of the system, which incorporates: (i) the distortion of the companion star, and its inhomogeneous surface brightness distribution; (ii) X-ray heating of the companion star; (iii) the effects of the presence of an accretion disk, which provides an additional source of optical light, partially or completely shields the companion star from X-rays, and can give rise to mutual eclipses with the companion star. This model has been used with some success to describe the optical light curves of Cen X-3 and SMC X-1 (Tjemkes et al., 1986). Our model differs from that of Khruzina and Cherepashchuk (1984) in that we include

Send offprint requests to: L. Kuiper (present address)

* Present address: SRON Laboratory for Space Research, Niels Bohrweg 2, 2333 AL Leiden, The Netherlands

the effect of the finite thickness of the accretion disk, which strongly influences the amount of X-ray heating of the secondary.

In applying this model to LMC X-3 we have chosen the model parameters to be consistent with all observed properties of LMC X-3. From the requirement that amplitudes $A_{0.0}$ and $A_{0.5}$ of the observed light curve be reproduced by the model we can derive constraints on the model parameters, which can be translated into a constraint on the mass of the compact star in LMC X-3.

In Sect. 2 we give a brief outline of the model, and describe how the model parameters have been chosen. In Sect. 3 we describe the results of our calculations, compare these with the observed light curve of LMC X-3, and derive constraints on the model parameters (and on the mass of the compact star). A brief summary of our conclusions is given in Sect. 4.

2. The model

The model we have used to compute the theoretical light curves has been described in detail by Zuiderwijk (1979) and Tjemkes, et al., (1986). The calculation consists of a numerical integration of the total flux from the companion star and the accretion disk, for a series of orbital phases at intervals of 0.05 cycles. The flux calculation is carried out by defining a grid of surface elements on the companion star and the accretion disk, and adding the contributions to the flux from the surface elements which are visible to the observer (taking into account possible mutual eclipses of the companion and the disk).

We have assumed that the shape of the companion star is that of a Roche equipotential surface. This implies that the orbit is circular, and the companion star is co-rotating with the orbit. In view of the high mass transfer rate, inferred from the high X-ray luminosity ($\sim 10^{38}$ erg s $^{-1}$), and the fact that an accretion disk is likely to be present (see Van Paradijs et al., 1987) we have assumed that the companion fills its critical Roche lobe (actually, to improve the numerical stability, we have assumed slight underfilling of the Roche lobe, by an amount corresponding to a fractional difference of $\sim 10^{-6}$ of the surface potential with respect to its critical value). The surface brightness distribution of the companion star (in the absence of X-ray heating) is described with Von Zeipel's theorem.

In modelling the X-ray heating of the companion star we assumed that a fraction $(1-\eta)$ of the infalling X-ray flux is absorbed, and a fraction η (the albedo) is reflected. The absorbed X-rays are re-radiated at lower energy, which gives rise to an increase of the (local) effective temperature. For η we have adopted the values 0.3 and 0.5 (see Milgrom and Salpeter, 1976; London, et al., 1981).

In view of our meagre understanding of X-ray irradiated accretion disks, we have used a very simple disk model: the disk is described by a flat cylinder, with a radius $R_d = \alpha R_L$ where R_L is the effective radius of the Roche lobe of the X-ray source, and height H_d above the orbital plane. Based on the calculations of accretion disks of Paczynski (1977) we have limited our calculations to $\alpha = 0.8$, and $\alpha = 1.0$. The circular upper (and lower) surface of this cylinder is assumed to radiate uniformly and isotropically (in the optical) as a black body; the outer edge of the cylinder is assumed not to radiate.

The parameters of the model are the mass M_{opt} and bolometric luminosity L_{opt} of the companion star, the mass ratio $q_X = M_X/M_{\text{opt}}$ the inclination angle i of the orbital plane, the blackbody temperature T_d of the accretion disk, the X-ray

luminosity l_X , the (half) angular thickness of the disk ($\gamma = \arctan H_d/R_d$), and the X-ray albedo η . We have varied γ between 2.5° and 15° . Except for γ and η (which are free parameters) these parameters are constrained by observable properties of LMC X-3.

The mass of the companion follows from the assumption that this star fills its Roche lobe, by combining Kepler's third law and the expression (Paczynski, 1971) for the ratio of the companion star radius to the distance, a , between the two stars (appropriate for $q_X > 1$; see Cowley et al., 1983), which yields $M_{\text{opt}} = 4\pi^2 3^4 R_{\text{opt}}^3 / (2^3 GP^2)$. Here P is the orbital period. Following Paczynski (1983) we have derived the radius of the companion star from its absolute visual magnitude, and a relation between the intrinsic colour index $(B-V)_0$ and visual surface brightness (Popper, 1980). We have adopted for the reddening-corrected ($E_{B-V} = 0.06$) apparent visual magnitude $V_0 = 17.32$ (Van Paradijs et al., 1987). For $(B-V)_0$ and the average effective temperature of the companion star we used the ranges from -0.20 to -0.08 , and from 15,400 K to 24,000 K, respectively, corresponding to spectral types between B1V and B5V. This range in $(B-V)_0$ is consistent with the $B-V$ values during the faintest observed optical state of LMC X-3, which is assumed to correspond to the "naked" companion star (Van Paradijs et al., 1987).

Because of the large range in recent determinations of the distance to the Large Magellanic Cloud (see e.g. Schommer et al., 1984; Schmidt, 1984; Visnavathan, 1985; Walker, 1985; Chiosi and Pigatto, 1986) we have done all calculations for three assumed values of this distance (40, 50 and 60 kpc). The corresponding ranges in the mass of the companion star are $\sim 0.5-1.5 M_\odot$, $\sim 1.0-3.0 M_\odot$, and $\sim 1.5-4.8 M_\odot$, respectively.

For a chosen value of M_{opt} the observed mass function (Cowley et al. 1983) defines a relation between the mass ratio q_X and inclination angle i .

The bolometric luminosity of the companion star is determined, once the radius (and mass) of the secondary and the distance have been chosen, by the requirement that the apparent visual magnitude of the companion $V_0 = 17.32$. In relating V_0 and L_{opt} we have used the relation between effective temperature and bolometric correction given by Popper (1980).

The blackbody temperature of the accretion disk is determined by the requirement that the apparent visual magnitude of the disk (which also depends on the disk radius and the orbital inclination) equals $V_d = 17.80$ (then the orbitally averaged total visual magnitude of LMC X-3 equals that observed during December 1984, when the X-ray observations were made; this value does not include a correction for interstellar absorption).

In determining the X-ray luminosity of LMC X-3 we have made two assumptions about the geometry of the X-ray emitting region, i.e. spherical and planar. The X-ray luminosity is then given by $L_X = 4\pi d^2 F_X$ (spherical) and $L_X = \pi d^2 F_X / \cos i$ (planar), respectively. For the X-ray flux F_X we used the average value observed with EXOSAT, i.e. $F_X = 1.0 \cdot 10^{-9}$ erg cm $^{-2}$ s $^{-1}$. The heating effect on the companion star is of course affected by the geometry of the X-ray emission.

3. Results

In this section we describe the results of our calculations of theoretical light curves of LMC X-3, using the model described in Sect. 2. We will first present the results for calculations made with

$f(M) = 2.3 M_{\odot}$, an assumed spherical geometry of the X-ray emitting region, and a disk radius equal to the average radius of the Roche lobe of the compact star. Then the effects of changing the value of the mass function, and of the radius of the accretion disk, and of assuming planar X-ray emission will be discussed.

We will represent the system by a point in the $(\log q_x, i)$ plane. As is apparent from the discussion in Sect. 2, for a given pair $(\log q_x, i)$ and an assumed source distance all parameters used in the calculation, except θ and η , are then defined through the requirement that observed properties of the system are reproduced.

The points in the $(\log q_x, i)$ plane for which we calculated light curves, are located along lines for which M_{opt} is constant (see Fig. 1). For a chosen pair of values (η, γ) acceptable solutions of the theoretical light curves have been obtained by first requiring that along an $M_{\text{opt}} = \text{constant}$ track the calculated values of $A_{0.0}$ and $A_{0.5}$ are within the observed ranges. By connecting the stretches of curves for constant M_{opt} (within the range in M_{opt} for

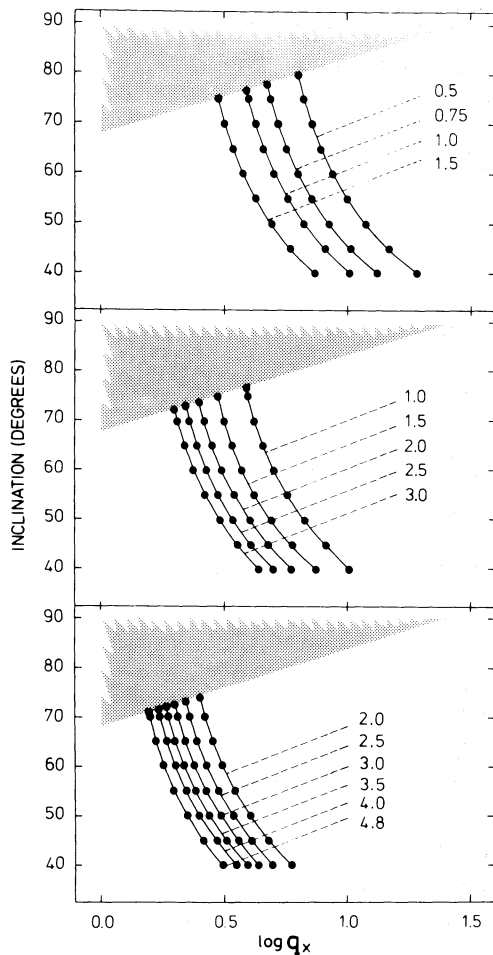


Fig. 1. Three $(\log q_x, i)$ diagrams, for distances of 40 kpc (upper panel), 50 kpc (middle panel), and 60 kpc (lower panel), indicating combinations of system parameters for which light curves have been calculated. The points representing the model parameters are located along lines $M_{\text{opt}} = \text{constant}$ (the value of M_{opt} is indicated for each drawn line). In these diagrams it has been assumed that the mass function $f(M) = 2.3 M_{\odot}$. The grey areas indicate parameter regime that is excluded by the observed lack of X-ray eclipses

the chosen distances), for which the observed amplitudes are reproduced, we obtain two bands in the $(\log q_x, i)$ plane, one for $A_{0.0}$, and one for $A_{0.5}$. The overlapping area of these two bands gives a region in the $(\log q_x, i)$ plane (“solution box”, see Fig. 2) in which, for the chosen pair of values (η, γ) , both amplitudes $A_{0.0}$ and $A_{0.5}$ are reproduced.

It should be noted that for theoretical curves with the correct amplitudes, the variations in η and γ are not independent. For a fixed value of η the disk thickness γ varies monotonically as a function of the secondary mass. This is not surprising, since both γ and η determine the extent to which the secondary is heated by infalling X radiation. Therefore, variation of η gives rise to a change of the location of the solution box in the $(\log q_x, i)$ plane along a single track, along which γ varies. These tracks, which are shown in Fig. 3 for the three adopted values of the distance, represent the final constraint on the system parameters of LMC X-3 which we obtain from our analysis of its optical light curve. It can be seen from Fig. 3 that this constraint corresponds to a rather narrow range in the inclination angle, roughly between 65° and 69° .

The corresponding ranges in the mass of the compact object are given in Table 1. We can approximately summarize these results by expressing the allowed range of M_x as $(4.5-6.5) (d/50 \text{ kpc}) M_{\odot}$.

To study the sensitivity of this range of M_x to the assumed value of the mass function we repeated the calculations for $f(M) = 2.0 M_{\odot}$, i. e. the $1-\sigma$ lower limit given by Cowley et al. (1983). Since we are particularly interested in the lower limit to the mass of the compact star we did the calculations only for a distance of 40 kpc. We find (see Table 1) that the range of M_x , allowed by the observed light-curve amplitudes, decreases by approximately 10% from $3.8-5.2 M_{\odot}$ to $3.4-4.7 M_{\odot}$.

In the above calculations we have assumed that the X rays are emitted spherically. Since LMC X-3 may be a black hole, most of the X rays could come from the inner accretion disk. We have therefore made some calculations for an assumed flat X-ray

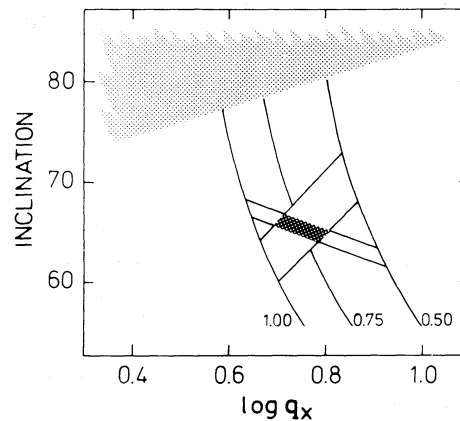


Fig. 2. The requirement that the amplitudes of the optical light curve are reproduced (to within their accuracy) by the theoretical curves defines two (not necessarily overlapping) segments along an $M_{\text{opt}} = \text{constant}$ curve (values are indicated) in the $(\log q_x, i)$ diagram. By varying the value of M_{opt} these segments move in the diagram, thereby forming two bands. Where these two bands overlap we have a small region (“solution box”) in the diagram where both observed amplitudes are reproduced. This figure is for assumed spherical X-ray emission, and values $f(M) = 2.3 M_{\odot}$, $d = 40 \text{ kpc}$, $\eta = 0.3$, $\gamma = 6.25^\circ$, $\alpha = 1.0$

Table 1. Limits on the masses of the components of LMC X-3

Distance (kpc)	$f(M)$ (M_\odot)	η	α	Symmetry ^a	M_{opt} (M_\odot)	M_X (M_\odot)
40	2.0	0.3	0.8	S	0.5–1.5	3.27–4.43
40	2.0	0.3	0.8	F	0.5–1.5	3.15–4.43
40	2.0	0.3	1.0	S	0.5–1.5	3.42–4.69
40	2.0	0.3	1.0	F	0.5–1.5	3.26–4.58
40	2.0	0.5	1.0	S	0.5–1.5	3.38–4.69
40	2.0	0.5	1.0	F	0.5–1.5	3.22–4.53
40	2.3	0.3	1.0	S	0.5–1.5	3.79–5.26
40	2.3	0.5	1.0	S	0.5–1.5	3.75–5.08
50	2.3	0.3	1.0	S	1.0–3.0	4.37–6.56
50	2.3	0.5	1.0	S	1.0–3.0	4.37–6.49
60	2.3	0.3	1.0	S	2.0–4.8	5.38–7.78
60	2.3	0.5	1.0	S	2.0–4.8	5.38–7.87

^aS indicates a spherical X-ray emitter, F indicates a flat X-ray emitter.

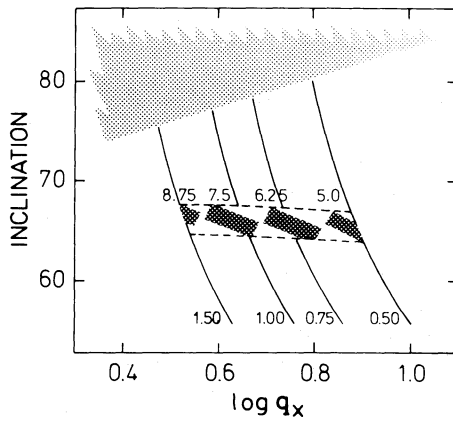


Fig. 3. Solution boxes in the $(\log q_x, i)$ diagram as a function of γ (thickness of the accretion disk). This figure is for spherical X-ray emission, $f(M) = 2.3 M_\odot$, $d = 40$ kpc, $\eta = 0.3$, $\alpha = 1.0$. It appears that, approximately independent of γ , the inclination angle is limited between $\sim 64^\circ$ and $\sim 67^\circ$. The corresponding limits on M_X are 3.8 and $5.3 M_\odot$ (see also Table 1)

source, located in the orbital plane, emitting isotropically. The results of these calculations (see Table 1) show that the values of M_X , for assumed planar X-ray emission, decrease by an additional $\sim 4\%$, as compared to the values obtained for a spherical X-ray emitter.

To study the sensitivity of our results to the assumed value of the disk radius we made a series of calculations, using an assumed disk radius of 80% of the average radius of the Roche lobe of the secondary star (i.e. near the size of the largest non-intersecting streamlines of particles leaving the companion star through the inner Lagrangian point; see Paczynski 1977). We find that the allowed range in M_X decreases by another $\sim 4\%$.

The combined effect of decreasing the mass function (to $2.0 M_\odot$), changing the X-ray geometry from spherical to planar, and decreasing the disk radius by 20%, is to decrease the allowed range in M_X by $\sim 17\%$.

4. Discussion

We have made a series of calculations of the optical light curve of LMC X-3, using a simple geometric model of the binary system, incorporating tidal and rotational distortion of the companion star, X-ray heating, and various effects of an accretion disk; the parameters of this model have been chosen consistently with other observed system properties. From the requirement that the observed amplitudes $A_{0.0}$ and $A_{0.5}$ be reproduced by our model we have found a constraint on the mass M_X of the compact star in LMC X-3.

For an assumed value of $2.3 M_\odot$ for the mass function, spherical X-ray emission, and an accretion disk which fills the Roche lobe of the compact star, the allowed range in M_X can be described approximately by $(4.5-6.5) (d/50 \text{ kpc}) M_\odot$, where d is the distance.

We have studied the sensitivity of this result to variations in the mass function and disk radius, and to the geometry of the X-ray emitting region. We find that a moderate relative change in the mass function (by $\sim 15\%$) leads to a somewhat smaller relative change ($\sim 10\%$) in M_X . A decrease of the disk radius by 20%, and a change from spherical to planar geometry of the X-ray emission, both lead to a decrease of m_X of $\sim 4\%$ (in the latter case the thickness of the disk is, of course, affected). For assumed values of the mass function and the distance of $1.7 M_\odot$ (2σ lower limit), and 40 kpc, respectively, the combined result of these changes is a lower limit on M_X of $2.8 M_\odot$. This lower limit is substantially larger than the corresponding value ($\sim 2 M_\odot$) derived by Mazeh et al. (1986), who did not use the information contained in the optical light curve. If we make the reasonable assumption that these small relative changes do not depend sensitively on the assumed distance, the corresponding lower limits on M_X are $3.2 M_\odot$, and $4.0 M_\odot$, for distance of 50 kpc, and 60 kpc, respectively.

It is of some interest to compare the above result with an estimate of the mass ratio that can be obtained from the observed rotational velocity of the companion star and its radial-velocity amplitude. For a synchronously rotating Roche-lobe filling star one has

$$V_{\text{rot}} \sin i / K_{\text{opt}} = R_{\text{opt}} / a_{\text{opt}} = 0.462 q_{\text{opt}}^{1/3} (1 + q_{\text{opt}})^{2/3} = f(q_{\text{opt}}) \quad (1)$$

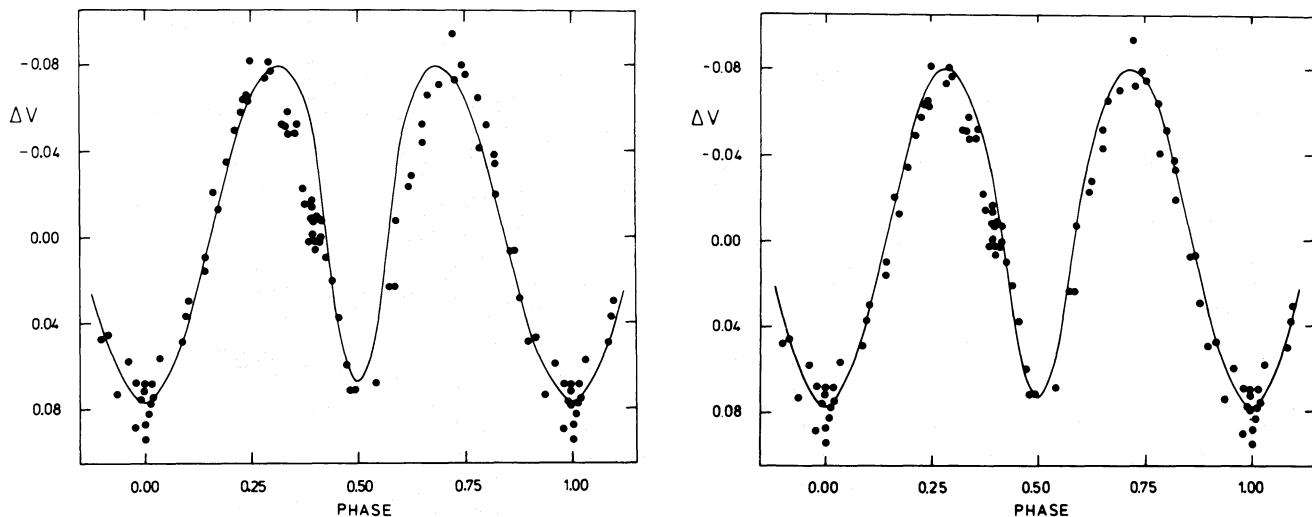


Fig. 4. Comparison of the observed light curve of LMC X-3 (data are indicated by dots) and two theoretical curves with the correct amplitudes. Upper panel: $d = 60$ kpc, $M_{\text{opt}} = 3.5 M_{\odot}$, $M_X = 6.73 M_{\odot}$, $i = 67.5^\circ$, $\eta = 0.5$, $\gamma = 10^\circ$, $\alpha = 1.0$, spherical X-ray emission. Lower panel: $d = 40$ kpc, $M_{\text{opt}} = 1.0 M_{\odot}$, $M_X = 3.97 M_{\odot}$, $i = 67.5^\circ$, $\eta = 0.3$, $\gamma = 4^\circ$, $\alpha = 1.0$, planar X-ray emission

Here a_{opt} is the radius of the (assumed circular) orbit of the companion star around the center of mass of the system, and $q_{\text{opt}} = M_{\text{opt}}/M_X = q_X^{-1}$. The assumption of synchronous rotation is reasonable, since for a Roche-lobe filling early-type star the time scale for synchronization of the spin and orbital frequencies is $\sim 10^6$ yr (Savonije and Papaloizou, 1982), which is much smaller than both the main-sequence lifetime of a B3 star, and the characteristic time scale of mass transfer (at a mass transfer rate of $\sim 10^{-8} M_{\odot} \text{ yr}^{-1}$). Furthermore, from the expressions given by Savonije and Papaloizou (1982) it appears that the time scale for synchronization is probably smaller than that for circularization of the orbit. As the orbit is very close to circular (in view of the absence of strong variability of the X-ray flux on the orbital time scale) synchronous rotation of the companion star of LMC X-3 appears to be a reasonable assumption. From the observed values $V_{\text{rot}} \sin i = 130 \pm 20 \text{ km s}^{-1}$, and $K_{\text{opt}} = 235 \pm 11 \text{ km s}^{-1}$ (Cowley et al., 1983) we find $f(q_{\text{opt}}) = 0.55 \pm 0.09$, with a corresponding 2σ lower limit on q_{opt} of 0.31 [From the data collected in Uesugi's (1976) catalogue it appears that the contribution of other broadening mechanisms, e.g. macroturbulence, is probably very small for LMC X-3.] Together with the range in inclination angle allowed by our above light-curve analysis (~ 64 to 70°), and a 2σ lower limit of $1.7 M_{\odot}$ on the mass function this leads to a lower limit on M_X of $3.5 M_{\odot}$, consistent with the above derived results.

The lower limit of $2.8 M_{\odot}$ on M_X , inferred from the optical light curve, is substantially larger than the maximum mass of a neutron star allowed by realistic neutron-star models ($\sim 2.5 M_{\odot}$, see e.g. Arnett and Bowers, 1977), and much larger than observed masses of neutron stars ($< 1.5 M_{\odot}$; see Rappaport and Joss, 1983). This limit is also close to the upper limit of $\sim 3.0 M_{\odot}$, which can be derived on the assumptions that general relativity is valid, and causality holds (Nauenberg and Chapline, 1973; Hartle, 1978).

As the lower limit of $2.8 M_{\odot}$ is rather extreme, in that it reflects our effort to push the model parameters such that a low value of M_X results, we conclude that the compact star in LMC X-3 is likely a black hole.

Our analysis is based on a comparison of theoretical and observed amplitudes; do theoretical curves with the correct amplitudes fit the shape of the whole observed light curve? To address this question we have made a number of additional calculations, for model parameters which according to the above analysis give the correct amplitudes $A_{0,0}$ and $A_{0,5}$. We find that some of these theoretical light curves fit the shape of the observed light curve in a fairly detailed fashion, whereas others show a substantial mismatch (see Fig. 4 for examples). It appears that discrepancies between the shapes of the observed and the theoretical light curves occur mainly between phases 0.25 and 0.75, i.e. when the compact star and the accretion disk are in front of the companion. This probably reflects the fact that in this phase interval the brightness of the system is most sensitive to details of the disk geometry, since a sizeable fraction (typically 20%) of the companion star is eclipsed by the accretion disk, but hardly any eclipsing occurs of the disk by the companion. Therefore, uncertainties in the net effect of the disk thickness on the total brightness, through the interplay between X-ray heating of the companion star, and the fraction of the companion that is eclipsed by the disk, are expected to count most heavily in this phase interval.

The firmness of our conclusion that the compact star in LMC X-3 is likely a black hole depends strongly on how well we understand systematic effects in the observational data underlying the present analysis. These include systematic uncertainties in the distance to the LMC, in the mass function of LMC X-3 (cf. Mazeh et al., 1986), and in its optical light curve (which depends on a separation of long-term from orbital effects, see Van Paradijs et al., 1987). We feel that improvement in these areas, which undoubtedly requires much observational effort, should precede attempts to refine the geometric description of LMC X-3 underlying our model calculations of the optical light curve.

References

- Arnett, W.D., Bowers, R.L.: 1977, *Astrophys. J. Suppl.* **33**, 415
Chiosi, C., Pigatto, L.: 1986, *Astrophys. J.* **308**, 1

- Code, A.D., Davis, J., Bless, R.C., Hanbury Brown, R.: 1976, *Astrophys. J.* **203**, 417
- Cowley, A.P., Crampton, D., Hutchings, J.B., Remillard, R., Penfold, J.E.: 1983, *Astrophys. J.* **272**, 118.
- Hartle, J.: 1978, *Physics Rep.* **46**, 201
- Khruzina, T.S., Cherepashchuk, A.M.: 1984, *Sov. Astron.* **28**, 173
- Leong, C., Kellogg, E., Gursky, H., Tananbaum, H., Giacconi, R.: 1971, *Astrophys. J. (Letters)* **170**, L67
- London, R., McCray, R., Auer, L.H.: 1981, *Astrophys. J.* **243**, 970
- Mazeh, T., Van Paradijs, J., Van den Heuvel, E.P.J., Savonije, G.J.: 1986, *Astron. Astrophys.* **157**, 113
- McClintock, J.E.: 1987 in *The Physics of Accretion onto Compact Objects*, eds. K.O. Mason, M.G. Watson and N.E. White, Lecture Notes in Physics, Vol. 266, (Springer Verlag), p. 211
- Milgrom, M., Salpeter, E.E.: 1975, *Astrophys. J.* **196**, 583
- Nauenberg, M., Chapline, G.: 1973, *Astrophys. J.* **179**, 277
- Paczynski, B.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 183
- Paczynski, B.: 1977, *Astrophys. J.* **216**, 822
- Paczynski, B.: 1983, *Astrophys. J. Letters* **273**, L81
- Popper, D.M.: 1980, *Ann. Rev. Astron. Astrophys.* **18**, 115
- Rappaport, S., Joss, P.C.: 1983 in *Accretion-driven Stellar X-ray Sources*, eds. W.H.G. Lewin, E.P.J. van den Heuvel, (Cambridge University Press), p. 1
- Savonije, G.J., Papaloizou, J.C.: 1982, *Monthly Notices Roy. Astron. Soc.* **203**, 581
- Schmidt, E.G.: 1984, *Astrophys. J.* **285**, 501
- Schommer, R.A., Olszewski, E.W., Aaronson, M.: 1984, *Astrophys. J. Letters* **285**, L53
- Tjemkes, S.A., Zuiderwijk, E.J., Van Paradijs, J.: 1986, *Astron. Astrophys.* **154**, 77
- Treves, A., Belloni, T., Chiapetti, L., Maraschi, L., Stella, L., Tanzi, E.G., Van der Klis, M.: 1988, *Astrophys. J.* **325**, 119
- Uesugi, A.: 1976, *Revised Catalogue of Stellar Rotation Velocities*, Kyoto University
- Van der Klis, M., Tjemkes, S., Van Paradijs, J.: 1983, *Astron. Astrophys.* **126**, 265 (1984, *Astron. Astrophys.* **132**, 240, Erratum)
- Van der Klis, M., Clausen, J.V., Jensen, K., Tjemkes, S., Van Paradijs, J.: 1985, *Astron. Astrophys.* **151**, 322
- Van Paradijs, J., Van der Klis, M., Augusteijn, T., Charles, P.A., Corbet, R.H.D., Ilovaisky, S.A., Maraschi, L., Motch, C., Pakull, M., Smale, A.P., Treves, A., Van Amerongen, S.: 1987, *Astron. Astrophys.* **184**, 201
- Visnavathan, N.: 1985, *Astrophys.* **288**, 182
- Walker, A.R.: 1984, *Monthly Notices Roy. Astron. Soc.* **212**, 243
- Warren, P.R., Penfold, J.E.: 1975, *Monthly Notices Roy. Astron. Soc.* **172**, 41P
- Zuiderwijk, E.J.: 1979, Ph.D. Thesis, University of Amsterdam