Evolutionary models of the optical component of the LMC X-1/Star 32 binary system

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ABSTRACT
Calculations carried out to model the evolution of Star 32 under different assumptions about the stellar wind mass-loss rate provide robust limits on the present mass of the star. The obtained range is 31 to 35.5 M\textsubscript{\odot}, which is in very good agreement with the orbital solution of Orosz et al., namely 28.3 to 35.3 M\textsubscript{\odot}. The initial mass of Star 32 had to be in the range 35 to 40 M\textsubscript{\odot}, and the present age of the system is 3.7 to 4.0 Myr.

Key words: binaries: general – stars: evolution – stars: individual: LMC X-1 – stars: massive – X-rays: binaries.

1 INTRODUCTION
LMC X-1 was one of the first X-ray binaries to be discovered, and the first one found in the Magellanic Clouds (Mark et al. 1969). The X-ray source is persistent, although variable, the luminosity varying by one order of magnitude (Liu, van Paradijs & van den Heuvel 2005). The source is very bright (L\textsubscript{X} \sim 1 - 2 \times 10^{38} \text{erg s}^{-1}, Johnston, Bradt & Doxsey 1979). Its X-ray spectrum was found to be relatively soft (kT \sim 2.7 keV, Markert & Clark 1975), which prompted Hutchings, Crampton & Cowley (1983, hereafter H83) to notice that it was similar to the two then known black hole candidates: Cyg X-1 and LMC X-3. The optical identification was firmly determined only quite recently (Cowley et al. 1995). The difficulty with the identity of the optical counterpart was that there were two comparably good candidates. Initially the bright (V = 12.0) B5 supergiant R148 was favoured as the counterpart (Jones, Chetin & Liller 1974; Rapley & Tuohy 1974; Johnston et al. 1979). The other, less favoured candidate was the fainter (V \approx 14.5) star denoted by Cowley et al. (1978) as Star no. 32. This star was observed spectroscopically by Pakull (1980), who noticed that the spectra ‘show He II 468.6-nm and N III-C III 464-465-nm emissions with strength comparable to that seen in most massive X-ray binary systems’. Both optical candidates were found spectroscopically by Hutchings et al. (1983). They found no detectable periodic variability for R148, but radial velocity measurements of Star 32 have shown it to be a binary with an orbital period of approximately 4 d. Two equally good fits to the observations were obtained for values of the period equal to 3.908 and 4.038 d. The authors also measured the velocities of emission lines, discovered by Pakull, which were found to vary in antiphase with the lines of Star 32. These lines probably originated near the secondary (compact) component, and, from the relative amplitudes, the authors deduced that the mass ratio (defined as the mass of the optical to the mass of the compact component) should exceed 2. The estimated most likely masses of the components were about \sim 14 and \sim 4 M\textsubscript{\odot}, which suggested that the secondary may be a black hole. White & Marshall (1984) noticed that the very soft X-ray spectrum of LMC X-1 places it close to other black hole candidates such as LMC X-3 and Cyg X-1 in an X-ray colour–colour diagram. After further optical spectroscopy, Hutchings et al. (1987, hereafter H87) refined the orbital period to 4.2288 d, and the masses of the components to 20 and 6 M\textsubscript{\odot}. The evidence that Star 32 is indeed the optical counterpart of LMC X-1 looked quite strong, but it was firmly established only after Cowley et al. (1995) compared the position of Star 32 with the position of LMC X-1 from ROSAT observations. In 2006, Levine & Corbet found the X-ray orbital period from data from RXTE. Their period was equal to 3.9081 ± 0.0015 d, which was somewhat shorter than the then accepted H87 period (4.2288 d), but was equal to one of the original (1983) propositions of H83.

In 2005 I calculated the preliminary evolutionary tracks modelling the evolution of Star 32 (Ziółkowski 2006). I found that the present mass of this star should be in the range 24 to 33 M\textsubscript{\odot}. However, this result was difficult to reconcile with the then available spectroscopic data. The reason was as follows.

We can estimate the radius R\textsubscript{opt} of the optical component from the observationally determined luminosity and the effective temperature. For spectral type O7 III (H83) we have T\textsubscript{\ast} \approx 36000 K and B.C. \approx -3.50. H83 estimated reddening as E(B - V) \approx 0.35, which implies A\textsubscript{B} \approx 1.1. With V \approx 14.8 and the distance modulus to the Large Magellanic Cloud (LMC) equal to 18.5 we have M\textsubscript{opt} \approx -8.3 or log (L/L\textsubscript{\odot}) \approx 5.2. With this luminosity and effective temperature, one obtains R\textsubscript{opt} \approx 10.5 R\textsubscript{\odot}.

If we assume the mass of the optical component M\textsubscript{opt} to be a free parameter, then after selecting its value we can use two equations to solve for the inclination of the orbit i and the mass ratio...
\[ q = \frac{M_{\text{opt}}}{M_\odot} \] (where \( M_\odot \) is the mass of the compact component).

One of these equations makes use of the mass function:

\[ f(M) = \frac{\sin^3 i}{[q(1 + q)]}. \tag{1} \]

The other relates the radius of the star to the size of the orbit:

\[ R_{\text{opt}} = R_{\text{RL}} f_{\text{RL}} \]
\[ = f_{\text{RL}}(0.38 + 0.2 \log q) A \]
\[ = f_{\text{RL}}(0.38 + 0.2 \log q) a_1(1 + q), \tag{2} \]

where \( R_{\text{RL}} \) is the radius of the Roche lobe (e.g. Paczyński 1971) around Star 32, \( f_{\text{RL}} \) is the fill-out factor \( (f_{\text{RL}} = R_{\text{opt}}/R_{\text{RL}}) \), \( A \) is the orbital separation of the binary components and \( a_1 \) is the radius of the orbit of Star 32.

Moreover, after H87, the (then accepted) values of the orbital period \( (4.2288 \, \text{d}) \) and of the radial velocity amplitude \( (K_{\text{opt}} = 69 \, \text{km} \, \text{s}^{-1}) \), one has \( f(M) = 0.144 \, \text{M}_\odot \) and \( a_1 \sin i = 5.76 \, \text{R}_\odot \) for the mass function and the radius of the orbit of the optical component, respectively.

Inserting these data, equations (1)–(2) can be written as

\[ M_{\text{opt}} \sin^3 i /[q(1 + q)]^2 = 0.144, \tag{3} \]

\[ R_{\text{opt}} = f_{\text{RL}}(0.38 + 0.2 \log q)(1 + q) \times 5.76/\sin i. \tag{4} \]

Recall that both H83 and H87 indicate that the surface of the star must be near the Roche limiting surface \((f_{\text{RL}} \geq 0.9)\). Then, solving equations (3)–(4) for \( i \) and \( q \), it is easy to verify that the observational condition \( q \geq 2 \) (H83) can be satisfied only for \( M_{\text{opt}} \lesssim 8 \, \text{M}_\odot \) if \( f_{\text{RL}} = 0.95 \), or for \( M_{\text{opt}} \lesssim 9.5 \, \text{M}_\odot \) if \( f_{\text{RL}} = 0.9 \). Allowing for observational errors, one might increase these upper limits slightly for the value of \( M_{\text{opt}} \), but this would not bridge the gap between the orbital solution \( (M_{\text{opt}} \lesssim 8 \quad \text{or} \quad 9 \, \text{M}_\odot) \), as shown above and the evolutionary constraints \( (M_{\text{opt}} \gtrsim 24 \, \text{M}_\odot) \).

Therefore, I concluded my 2006 considerations with the statement ‘There are only two possible solutions of this discrepancy: either observations of Star 32 (spectroscopy and/or photometry) are in serious error or Star 32 is essentially a helium star (with only a small remnant of the hydrogen rich envelope)’. I concluded that future observations should solve this problem.

\section*{NEW ORBITAL SOLUTION}

Later observations did indeed solve the problem. Orosz et al. (2009) published a detailed analysis of their new extensive spectroscopic and photometric observations of Star 32 together with a refined analysis of the ASM data from RXTE observations of LMC X-1. Their new orbital solution greatly improved the earlier rough estimates, removed the puzzles (mass versus luminosity of the optical component) and produced a fairly consistent picture of the binary system.

First, they found that the optical orbital period is not \( 4.2288 \, \text{d} \) as was generally accepted after H87, but rather \( 3.99017 \pm 0.00005 \, \text{d} \), in agreement with the X-ray period suggested by Levine & Corbet (2006), and also with one of the two original orbital period candidates of H83. After a thorough analysis, they determined the masses of the components as \( M_{\text{opt}} = 30.62 \pm 3.22 \, \text{M}_\odot \) and \( M_\odot = 10.30 \pm 1.34 \, \text{M}_\odot \). They also determined quite precisely the luminosity and the effective temperature of Star 32 as \( \log(L/L_\odot) = 5.50 \pm 0.05 \) and \( T_\text{eff} = 33200 \pm 500 \, \text{K} \). They found that these values are consistent with the core hydrogen burning star of initial mass \( \sim 35 \, \text{M}_\odot \).

It thus became clear that the reasons for the dramatic discrepancy discussed in Ziolkowski (2006) were: (i) a serious (by a factor of 2) underestimate of the luminosity of Star 32; and (ii) an overestimate (by \( \sim 8.5 \) per cent) of its effective temperature. These two factors led to a serious (by \( \sim 40 \) per cent) underestimate of its radius (\( \sim 10.5 \, \text{R}_\odot \), instead of \( \sim 17 \, \text{R}_\odot \)). This small value for the radius of Star 32, together with the requirement that it should nearly fill its Roche lobe, led to an uncomfortably small mass of this star.

Note that even the underestimated luminosity of \( \log(L/L_\odot) \approx 5.2 \) was much too high for the mass of Star 32 proposed by H83 (\( \sim 14 \, \text{M}_\odot \)); and this relatively high value of the mass was achieved only by stretching the then observed value of the radius from \( \sim 10 \, \text{R}_\odot \) to \( \sim 12 \, \text{R}_\odot \).

After new precise data concerning the LMC X-1/Star 32 binary system became available, I decided to carry out new evolutionary calculations to determine more precisely the past evolution and the present evolutionary state of Star 32.

\section*{EVOLUTIONARY CALCULATIONS FOR STAR 32}

\subsection*{General description}

I computed evolutionary tracks for the core hydrogen-burning phase of stars with initial masses in the range 30–50 \( \text{M}_\odot \). The Warsaw evolutionary code developed by Bohdan Paczyński and Maciek Kozłowski and updated by Ryszard Sienkiewicz and Alosha Pamyatnykh was used. An initial chemical composition of \( X = 0.7 \) and \( Z = 0.008 \), appropriate for the LMC, was adopted. Opacity tables incorporating OPAL opacities (Iglesias & Rogers 1996) as well as molecular and grain opacities (Alexander & Ferguson 1994) were used. The nuclear reaction rates are those of Bahcall & Pinsonneault (1995). The equation of state used was that of Livermore Laboratory OPAL (Rogers, Svenson & Iglesias 1996). Semiconvective mixing was neglected, as it is not important during the evolutionary phase considered (most of the models of interest had central hydrogen content \( X_c \gtrsim 0.2 \)). Similarly, any overshooting at the border of the convective core was neglected, as this is even less important.

The calculations were carried out under the assumption that the evolution starts from homogeneous configurations. This means that the consequences of the fact that some of the matter of the star, possibly dumped from the progenitor of the present black hole, could have modified the chemical composition were neglected. It also means that the consequences of the fact that some nuclear evolution (hydrogen burning) could, possibly, have taken place while the mass of the star was smaller (prior to the mass transfer) were neglected as well. It seems that neither simplification significantly alters the outcome of the evolutionary calculations. The orbital period is so short that any substantial mass transfer during past evolution seems unlikely, as it would have led to a common envelope configuration and the merger of the two stars. Even if (which seems unlikely) there was significant mass transfer in the system, then it just reset the evolutionary clock and we can consider the evolution of the mass gained as starting anew from the zero-age main sequence (ZAMS), as a single star but with a higher mass.

\subsection*{Stellar wind mass loss}

The most uncertain element of the calculations of the early evolution of massive stars is the mass loss caused by the stellar wind. The uncertainty in the estimate of its rate is the single most important factor influencing the outcome of the calculations (see e.g. Ziolkowski 2005). The observations seem to indicate that there is
Evolutionary models of Star 32

Figure 1. The evolutionary tracks in the Hertzsprung–Russell diagram (solid lines). The dotted cross shows the observed position of Star 32. The number at the start of each track indicates the initial mass (in solar units). The numbers near the cross indicate the mass at the evolutionary phase corresponding to the present state of Star 32. Part (a) shows the tracks obtained using the HPT formula to describe the stellar wind (see text); (b) shows tracks obtained using formula (5); (c) shows tracks obtained using formula (6); and (d) shows tracks obtained using formula (7). The value of the parameter $f_{\text{now}}$ (see text) used for each track is given in Table 1.

A substantial scatter of mass-loss rate among stars of similar luminosities and effective temperatures. The commonly used formula derived by Hurley, Pols & Tout (2000, hereafter HPT), based on parametrization of Nieuwenhuijzen & de Jager (1990), gives the estimate of the mass-loss rate with an accuracy that is probably not better than a factor of two. Bearing this in mind, I introduced the multiplicative factor $f_{\text{SW}}$ applied to the HPT formula. In this way, the uncertainty in the theory of evolution could be, in some way, taken into account.

The value of the factor $f_{\text{SW}}$, which should be used to model successfully the evolution of a given star, might be quite different for seemingly similar stars. For some cases (e.g. HDE 226868, which is the companion to Cyg X-1), this value is close to 1 (Ziolkowski 2005). However, in some high-mass X-ray binaries, the optical supergiant components are significantly under-massive for their luminosities (Ziolkowski 1977). In some systems, such as Cen X-3, this undermassiveness is very serious and requires much stronger mass loss than the normal HPT stellar wind (Ziolkowski 1978). It seems that Star 32 is probably (as we shall see) closer to the case Cen X-3 than to HDE 226868, in this respect.

The evolutionary calculations carried out to produce models reproducing the present evolutionary state of Star 32 and using the HPT formula are quite successful (see Fig. 1a), except for one aspect: the value of the stellar wind mass-loss rates predicted by these models are too small by almost an order of magnitude when compared with the observations (see Table 1). The observed value $\dot{M} \approx -5 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ was determined by Orosz et al. (2009) from analysis of the orbital X-ray light curve. They modelled the light curve successfully, assuming that variability is due to the scattering of X-ray photons by electrons in the stellar wind over the variable (with the orbital phase) optical depth in the wind. This estimate agrees roughly with the one derived from the observed X-ray luminosity. It should be noted, however, that this estimate, being model-dependent, is not as robust as the determinations of the parameters of the system and its uncertainty might be quite large.

The observed value of $\dot{M}$ seems to be substantially (by a factor of $\sim 6$–8) larger than the value predicted by the HPT formula for the present parameters of Star 32. It is clear, therefore, that to model the evolution of Star 32 (including its present mass-loss rate) successfully it is necessary to modify the HPT formula, increasing significantly the strength of the stellar wind; that is, to use values of the factor $f_{\text{SW}}$ that are substantially larger than 1. I have tried three such modifications:

$$f_{\text{SW}} = f_{\text{now}},$$

$$f_{\text{SW}} = 1 + (f_{\text{now}} - 1)(R - R_{\text{ZAMS}})/(R_{\text{cr}} - R_{\text{ZAMS}}),$$
The mass of Star 32 must be in the range 31 to 35.5 M\(^\odot\), according to our evolutionary sequences. The present mass of Star 32 is then in the range 32 to 36 M\(^\odot\). The calculations modelling the evolution of Star 32, under different assumptions about the shape of the formula describing the stellar wind mass-loss rate, provide robust limits on the present mass of the star. For the reasonable versions of this formula, this mass should be in the range 31 to 35.5 M\(^\odot\).

(i) The initial mass of Star 32 had to be in the range 35 to 40 M\(^\odot\), stronger than the typical one (HPT) by a factor as high as 6–8. However, there are indications, dating from a long time ago (Zi\'olkowski 1977; Hutchings 1979), that the strength of the stellar wind from a component of a close binary system might increase significantly as the stellar surface approaches that of the Roche lobe. There is no quantitative description of this effect available. The formulae (6) and (7) try to incorporate it, in a crude way, by a linear or quadratic dependence on the distance from the Roche lobe.

### 3.3 Results

The evolutionary tracks in the Hertzsprung–Russell (HR) diagram, obtained with the unmodified HPT formula and with formulae (5)–(7), are shown in Figs 1a–d. All tracks reproduce the present luminosity and effective temperature of Star 32 well, and the tracks obtained with formulae (5)–(7) reproduce, in addition, the present mass flux of the stellar wind. The parameters of the models corresponding to the present state of Star 32 are given in Table 1. The variations of the stellar wind mass flux with the evolutionary time, for different evolutionary sequences, are shown in Fig. 2.

The summary of the results can be brief. Equation (5) does not seem to correspond to the true history of the stellar wind strength in the LMC X-1/Star 32 binary system (see the discussion in Section 3.2). The formulae (6) and (7) (although obtained ad hoc) seem to be much more realistic, and I believe that they give a crude but reasonable description of the evolution of the stellar wind mass flux from Star 32. The differences between the results obtained with formulae (6) and formula (7) are not significant (see Table 1 and Figs 1c and 1d), which makes our conclusions more robust. To conclude: The present evolutionary mass of Star 32 must be in the range 31 to 35.5 M\(^\odot\). This result is in very good agreement with the new orbital solution of Orosz et al. (2009), who give a range for the mass of the star of 28.3 to 35.3 M\(^\odot\). According to our evolutionary sequences, the initial mass of Star 32 had to be in the range 35 to 40 M\(^\odot\), and the present age of the system is 3.7 to 4.0 Myr.

In addition, note that if one disregards the estimate of \(\dot{M}\), as a not very reliable constraint, then one is left with sequences 1 and 2. The present mass of Star 32 is then in the range 32 to 36 M\(^\odot\), its initial mass is in the range 33.5 to 37.5 M\(^\odot\), and the present age of the system is in the range 3.9 to 4.2 Myr. As can be seen, the results are not very different. This confirms that our conclusions are not sensitive to the uncertainties of the mass-loss treatment.

### 4 CONCLUSIONS

(i) The calculations modelling the evolution of Star 32, under different assumptions about the shape of the formula describing the stellar wind mass-loss rate, provide robust limits on the present mass of the star. For the reasonable versions of this formula, this mass should be in the range 31 to 35.5 M\(^\odot\).

(ii) The initial mass of Star 32 had to be in the range 35 to 40 M\(^\odot\).

(iii) The present age of the system (counted from its birth or from the resetting of the evolutionary clock after the possible, but unlikely, mass transfer) is in the range 3.7 to 4.0 Myr.

(iv) The evolutionary estimate of the mass of Star 32 remains in very good agreement with the estimate based on the orbital solution of Orosz et al. (2009): 28.3 to 35.3 M\(^\odot\).

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