XMM-Newton Optical Monitor observations of LMC X-3

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Abstract. We study the optical counterpart of the black-hole X-ray binary LMC X−3, by using XMM-Newton/OM observations carried out during a low-hard X-ray state. We derive a better constraint for the temperature, mass and radius of the companion star, and we show that the star is likely to be a ~ B5 subgiant filling its Roche lobe. Taking into account the effect of X-ray irradiation, we suggest a value $f_M \approx 1.5M_\odot$ for the mass function in this system, lower than previously thought; we provide a more accurate lower limit to the mass of the compact object.

Key words: accretion, accretion disks – Black hole physics – binaries: general – stars: early type – X-rays: general

1. Introduction

An important unsolved problem for the black-hole candidate (BHC) LMC X−3 is the process of mass transfer. With an estimated mass of the companion star $\approx 1 M_\odot$, the system appears to be intermediate between high-mass black-hole binaries like Cyg X−1 (mass of the companion star $\approx 33 M_\odot$, see Giles & Bolton 1986), and low-mass black-hole binaries like A0620−00 (mass of the companion star $\approx 0.7 M_\odot$). In the former class of systems, mass transfer occurs mainly via a stellar wind, and the donor star is more massive than the primary; in the latter, the donor star is usually a late-type star filling its Roche lobe.

The optical counterpart (Warren and Penfold 1975) of LMC X−3 shows ellipsoidal modulations with a total amplitude of $\approx 0.2$ mag and a period corresponding to the 1.705d binary period (van der Klis, Tjemkes and van Paradijs 1983; van der Klis et al 1985). It also shows long-term brightness variations in the range $16.7 \lesssim V \lesssim 17.5$ (e.g., van Paradijs et al. 1987). Its optical spectrum was found to be consistent with that of a B3 main sequence star (Cowley et al. 1983). From the radial velocity shifts of the optical absorption lines, Cowley et al. (1983) derived a mass function $f_M = 2.3 M_\odot$, thus establishing this system as a strong BHC. However, the spectral identification of the companion star remains uncertain (Mazeh et al. 1986) because of the effect of X-ray irradiation on the secondary, and the possible contribution to the optical flux by an accretion disk. In fact, the long-term variations in both the optical colours and the $V$ brightness are found to be associated with changes in the soft X-ray flux (Cowley et al. 1991).

Moreover, Nowak et al. (2000) and Wilms et al. (2000) suggest that spectral transitions between a high-soft and a low-hard state could be associated with changes in the accretion rate. A more correct identification of the companion star can provide a better understanding of the physics of mass transfer and state transitions.

2. XMM-Newton Optical Monitor observations

LMC X−3 was observed with the Optical Monitor 30in telescope (Mason et al. 1996) on board XMM-Newton on 2000 April 19 (MJD 51653; XMM-Newton revolution 66). A log of the observations is reported in Table 1. The system was in a low-hard state during our optical observations, with a pure power-law X-ray spectrum with photon index $\approx 1.6$–1.8 (Boyd and Smale 2000; Wu et al. 2000). We estimate from simultaneous XMM-Newton/PN observations (Wu et al. 2000) that the 2–10 keV flux was $\lesssim 10^{-34}$ erg s$^{-1}$, at least two orders of magnitude lower than in the high-soft state (Nowak et al. 2000; Wilms et al. 2000). This is in agreement with the RXTE/ASM 2–10 keV lightcurve. Therefore, optical photometric observations of the companion star at this epoch provide the best chance to determine its intrinsic colours and spectral type.

3. Optical colours and temperature

The average brightness of LMC X−3 measured in the three XMM-Newton/OM optical bands on 2000 April 19 was $v = 17.48 \pm 0.02$, $b = 17.39 \pm 0.02$, $u = 16.56 \pm 0.02$. (For a detailed comparison between the XMM-Newton/OM photometric system and Johnson’s standard
In Figure 2 the evolutionary tracks (Girardi et al. 2000) are shown, with the mean density in the Roche lobe of the companion star, $\rho \approx 3\ M_\odot$, as calculated from the effective temperature $T_{\text{eff}}$ of the primary star. From the inferred range of luminosities and temperatures, we obtain a reliable constraint to the mass of the secondary star.

Figure 1 shows the single-star evolutionary tracks from Girardi et al. (2000) in the $(\log T_{\text{eff}}, \log L_{\text{bol}})$ plane, for a metal abundance $Z = 0.008$ (a typical value for the LMC, see, for example Caputo, Marconi and Ripepi 1999). Assuming that evolutionary tracks for stars in binary systems can be approximated by single-star tracks, we infer that the constraint is satisfied by evolved stars with $4.7 M_\odot \lesssim M_2 \lesssim 5.3 M_\odot$ corresponding to subgiant of spectral type $\sim$ B5. A B3 main sequence companion ($M_2 \approx 6 - 7 M_\odot$) has the correct luminosity but much higher temperatures. This result is not very sensitive to the adopted value of metal abundance.

### Table 1. Log of our XMM-Newton/OM observations

| OM filter | Mid-exposure time (MJD) | Exposure time (s) |
|-----------|-------------------------|------------------|
| v         | 51653.148               | 1000             |
| v         | 51653.178               | 1000             |
| v         | 51653.193               | 1000             |
| v         | 51653.208               | 1000             |
| u         | 51653.123               | 1000             |
| u         | 51653.238               | 1000             |
| u         | 51653.253               | 1000             |
| u         | 51653.268               | 1000             |
| u         | 51653.283               | 1000             |
| b         | 51653.298               | 1000             |
| b         | 51653.313               | 1000             |
| b         | 51653.328               | 1000             |
| b         | 51653.343               | 1000             |
| b         | 51653.358               | 1000             |

### 4. Radius of the companion star

The mean mass density in the Roche lobe of the companion star is uniquely determined by the orbital period $P$ (Frank, King and Raine 1992):

$$\rho \equiv \frac{3M_2}{4\pi R_L^2} \approx 115 P_{\text{hr}}^{-2} \approx 0.069 \text{ g cm}^{-3},$$

where $R_L$ is the mean radius of the Roche lobe. We plot in Figure 2 the evolutionary tracks (Girardi et al. 2000) in the $(M_V, \rho)$ plane, together with the mean density in the Roche lobe derived in Equation (1), for $Z = 0.008$. The dashed line corresponds to a radius of $0.95 R_L$. Stars with $4M_\odot \lesssim M_2 \lesssim 4.7 M_\odot$ would be very close to filling
their Roche lobe at the observed brightness $M_V$. If the companion star has a mass $M_2 = 4.7 M_{\odot}$, its radius would be $R_2 = 4.4 R_{\odot} \approx R_L$. Mass transfer would mainly occur via Roche-lobe overflow. Stars of lower mass would also fill their Roche lobe but are ruled out by the observed range of colours (Figure 1). On the other hand, if $M_2 > 4.7 M_{\odot}$, the companion star would not fill its Roche lobe. In particular, a B3V companion ($R_2 \approx 4 R_{\odot}$) would only fill less than half of the volume of its Roche lobe. The main mechanism of mass transfer would have to be a stellar wind. If the wind were to account for X-ray luminosities up to $\approx 4 \times 10^{38} \text{ erg s}^{-1}$ in the high-soft state (Johnston, Bradt and Doxsey 1979), the column density would be much higher than $10^{21} \text{ cm}^{-2}$, difficult to reconcile with the result obtained from the XMM-Newton X-ray observations (Wu et al. 2000).

The evolutionary time-scale for a subgiant star of mass $\approx 4.7 M_{\odot}$ in the observed range of temperature is $\approx 2 \times 10^7$ years (Girardi et al. 2000). If the mass transfer is driven by the nuclear evolution of the secondary, this would imply a mass-transfer rate $\approx 2 \times 10^{-7} M_{\odot}$ per year, sufficient to account for luminosities $\gtrsim 10^{39} \text{ erg s}^{-1}$.

5. A lower limit on the mass of the primary

The masses of the two components of a binary system are given by

$$M_X = \frac{(1+q)^2}{\sin^3 i} f_M, \quad \text{(2)}$$

$$M_2 = \frac{q(1+q)^2}{\sin^3 i} f_M, \quad \text{(3)}$$

where $q \equiv M_2/M_X$ and $f_M$ is the mass function of the primary, which can be obtained from spectroscopic observations. The X-rays are not eclipsed (Cowley et al. 1983); if the secondary star is approximated by a sphere, this implies (Paczyński 1983):

$$R_2 < K_2 \frac{P}{2\pi} (1+q) \cot i, \quad \text{(4)}$$

where $K_2$ is the projected radial velocity semi-amplitude of the secondary star. From equations (3) and (4), an upper limit for $q$ is obtained:

$$R_2 < K_2 P (2\pi)^{-1}(1+q)^{1/3} q^{-1/3} f_M^{-1/3} M_2^{1/3} \times \left[1 - q^{2/3}(1+q)^{4/3} f_M^{2/3} M_2^{-2/3}\right]^{1/2}, \quad \text{(5)}$$

where the right-hand side is a monotonically decreasing function of $q$ where defined.

From the radial velocity shifts of the stellar absorption lines, Cowley et al. (1983) determined $K_2 = 235 \pm 11 \text{ km s}^{-1}$ and $f_M = 2.3 \pm 0.3 M_{\odot}$. Using these values together with the values of $M_2$ and $R_2$ determined in Section 4, we obtain from equation (5):

$$M_X > 7.3 \pm 0.6 M_{\odot}. \quad \text{(6)}$$

As an aside, we also note that if we assume a lower limit $i > 50$ for the inclination angle (van der Kils et al. 1985), equation (2) gives an upper limit $M_X < 13.8 \pm 1.0 M_{\odot}$.

If the secondary star is really a B5 subgiant, its intrinsic luminosity is $\lesssim 3.5 \times 10^{36} \text{ erg s}^{-1}$ (Figure 1), corresponding to an intrinsic flux $F_2 \lesssim 3 \times 10^{12} \text{ erg cm}^{-2} \text{ s}^{-1}$. The radial velocity curve of the stellar absorption lines was obtained by Cowley et al. (1983) when the source was in a high state, implying an X-ray luminosity $L_X \gtrsim 10^{38} \text{ erg s}^{-1}$. The orbital separation in a binary system is $a = 2.9 \times 10^{11} M_1^{1/3} (1+q)^{1/3} P_d^{2/3} \approx 1.0 \times 10^{12} \text{ cm}^3$ for LMC X–3. Hence, the energy intercepted by the secondary star per unit time is $(1/4) L_X (R_2/a^2) \gtrsim 3 \times 10^{36} \text{ erg s}^{-1}$, comparable with the intrinsic luminosity of the star.

In a spherical approximations, the intercepted flux is larger than the intrinsic flux on $\approx 1/4$ of the surface of the star, for a soft X-ray luminosity $\approx 2 \times 10^{38} \text{ erg s}^{-1}$, and for a disk with $H/R \lesssim 0.2$. Strong external irradiation with soft X-rays tends to cause photo-ionisation at the surface of the secondary star. As a consequence, absorption lines from the irradiated face should be weakened or suppressed, and the observed radial velocity shifts may not reflect the true orbital motion of the centre of mass of the secondary (Wade and Horne 1988; Phillips, Shahbaz and Podsiałowski 1999). Using the model previously applied to the BHC GRO J1655–40 (Phillips, Shahbaz and Podsiałowski 1999), and assuming for simplicity that no absorption lines are produced in the region where the external flux is larger than the internal flux, we can estimate the effect of irradiation in the case of LMC X–3. The observed amplitude of the radial velocity variations of the absorption...
lines \((K_2)\) should appear larger than the true radial velocity amplitude of the centre of mass of the secondary \((K_2' = K_2 - \Delta K_2)\). For the parameters of LMC X–3, we estimate that the correction is \(\Delta K_2 = 30 \pm 5 \text{ km s}^{-1}\). Therefore, the true \(K\)-velocity of the secondary star is only

\[
K_2' = 205 \pm 12 \text{ km s}^{-1}. \tag{7}
\]

Hence, after the correction, the mass function \((\propto K_2^3)\) for the compact object in LMC X–3 is

\[
f_M = 1.5 \pm 0.3 M_\odot. \tag{8}
\]

By using these revised \(K\)-velocity and mass function in equation (5), we obtain a lower limit to the mass of the compact object:

\[
M_X > 5.8 \pm 0.6 M_\odot. \tag{9}
\]

It would be important to test this prediction by determining the radial velocity curve of the stellar lines during a low X-ray state. We also note that if the irradiated side of the secondary star contributes only to the optical continuum flux but not to the absorption lines, their relative strength would appear reduced in comparison with a non-irradiated star of the same spectral type. This is a possible explanation of what was observed by Cowley et al. (1983).

6. Conclusions

We have observed the BHC LMC X–3 with the Optical Monitor on board XMM-Newton during an X-ray low-hard state. The 2–10 keV flux at that epoch was the lowest ever observed by RXTE/ASM, consistent with zero. The brightness and colours of the optical counterpart inferred from our observations are likely to be a good approximation of the intrinsic values of the companion star. This allows us to constrain the mass and radius of the secondary. We have found that an evolved subgiant of mass \(M_2 \approx 4.7 M_\odot\) and temperature \(T_{\text{eff}} \approx 16500 \text{ K}\) (spectral type \(\sim B5\)IV) is consistent with the observed colours and luminosity. We have also shown that such a star would be filling its Roche lobe, thus explaining why the source is mostly observed in a high-soft state, dominated by an accretion disk. No significant wind is expected from such star, in agreement with the low column density inferred from the XMM-Newton/EPIC and RGS X-ray data. The evolutionary time-scale of a B5IV star is also consistent with the observed X-ray luminosity powered by nuclear-evolution driven mass transfer.

The companion star was previously thought to be a main-sequence B3 star. Although it would have the same brightness, a B3V star would fill only about one half of its Roche lobe, ruling out mass transfer via Roche-lobe overflow.

A B5IV companion implies a lower limit to the mass of the primary \(M_X > 7.3 \pm 0.6 M_\odot\), if we assume the \(K\)-velocity and mass function determined by Cowley et al. (1983). However, the spectroscopic observations of Cowley et al. (1983) were carried out during an X-ray active state, when the effect of soft X-ray irradiation on the surface of the secondary star is significant. The true radial velocity amplitude of the centre of mass of the secondary is probably \(12–15\) per cent less than the value observed by Cowley et al. (1983). This would reduce the mass function to \(f_M = 1.5 \pm 0.3 M_\odot\), and set a lower limit \(M_X > 5.8 \pm 0.6 M_\odot\) for the mass of the compact object.

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