Searching for periodicities in the MACHO light curve of LMC X–2

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ABSTRACT
Using the exceptional long-term monitoring capabilities of the MACHO project, we present here the optical history of LMC X–2 for a continuous 6-yr period. These data were used to investigate the previously claimed periodicities for this source of 8.15 h and 12.54 d: we find upper amplitude limits of 0.10 mag and 0.09 mag, respectively.

Key words: binaries: close - stars: individual: LMC X–2 - X-rays: stars.

1 INTRODUCTION
LMC X–2 was discovered in the Large Magellanic Cloud (LMC) by early satellite flights (Leong et al. 1971) which showed it to be a variable X-ray source with $L_x\sim (0.6–3) \times 10^{38}$ erg s$^{-1}$ (Markert & Clark 1975; Johnston, Bradt & Doxsey 1979; Long, Helfand & Grabelsky 1981). LMC X–2 is the most luminous low mass X-ray binary (LMXB) known. After its precise position was determined (Johnston et al. 1979), the optical counterpart was identified as a faint, $V \sim 18.8$, blue star similar to Sco X–1 (Pakull 1978; Pakull & Swings 1979).

Motch et al. (1985) found variations of $\sim 0.4$ mag in the optical light curve of LMC X–2, which were modulated on a period of 6.4 h (see also Bonnet-Bidaud et al. 1989). More extensive photometric observations obtained by Callanan et al. (1990) showed flickering of
~0.1 mag on timescales of \( \lesssim 0.5 \) h and ~0.3 mag variations on ~4 h timescales. Period searching revealed a period of \( 8.15 \pm 0.02 \) h with a semi-amplitude of ~0.08 mag which, being stable over their ~14 d observations, they interpreted as being orbital in origin. However, Crampton et al. (1990) did not detect the 8.15-h modulation, it implies that the amplitude of this modulation is itself variable on timescales \( \gtrsim 10 \) days. If it is owing to X-ray heating of the secondary, a semi-amplitude of 0.08 mag indicates that \( i \lesssim 70^\circ \) (van Paradijs, van der Klis & Pederson 1988).

1.1 Is the Orbital Period 8.15 h?

If an orbital period of 8.15 h is correct, we would expect a significant contribution from a heated secondary or outer disc bulge, and this should be evident from the shape of the folded light curve (Callanan et al. 1990). However, as Crampton et al. (1990) did not detect the 8.15-h modulation, it suggests that the amplitude of this modulation is itself variable on timescales \( \gtrsim 10 \) days. If it is owing to X-ray heating of the secondary, a semi-amplitude of 0.08 mag indicates that \( i \lesssim 70^\circ \) (van Paradijs, van der Klis & Pederson 1988).

1.2 Or is it 12.54 d?

If a 12.54-d period is correct, taking into account the structure and asymmetry of the light curve obtained, LMC X–2 would be similar to Cyg X-2 (Cowley, Crampton & Hutchings 1979). This would suggest that the variations in the LMC X–2 light curve might contain both a heated component and a partial eclipse of the accretion disc by the secondary. Irregularities in the disc could be a result of the extreme brightness of the accretion disc. This may be owing to the high luminosity fuelled by the higher rate of mass transfer allowed by the lower metal abundances in the LMC, leading to a higher Eddington luminosity (Russell & Dopita 1990). No correlation between X-ray and optical light curves has yet been detected that would help in the identification of the period.

We present here the results of ~6 years of optical monitoring of the source. These observations were acquired as a by-product of the MACHO project (Alcock et al. 1995a), owing to the serendipitous location of LMC X–2 in a surveyed field. Such extended monitoring is ideal for investigating modulations on timescales of tens of days.

2 OBSERVATIONS

The MACHO observations were made using the 1.27-m telescope at Mount Stromlo Observatory, Australia. A dichroic beamsplitter and filters provide simultaneous CCD photometry in two passbands, a ‘red’ band (~6300–7600 Å) and a ‘blue’ band (~4500–6300 Å). The latter filter is a broader version of the Johnson V passband (see Alcock et al. 1995a, 1999 for further details).

The images were reduced with the standard MACHO photometry code sodophot, based on point-spread function fitting and differential photometry relative to bright neighbouring stars. Further details of the instrumental set-up and data processing may be found in Alcock et al. (1995b, 1999), Marshall (1994) and Stubbs et al. (1993).

3 RESULTS

Using the absolute calibration of the MACHO fields the red and blue magnitudes were transformed to Johnson V and Cousins R passbands (Fig. 1). The data consist of MACHO project observations from 1992 November 1 to 1998 November 21. The sampling of the light curves increases at ~1800 d, when the MACHO observing strategy was modified to give increased weight to fields further from the LMC bar. This epoch coincides with the increase in the mean magnitude of LMC X–2.

To search for periodicities, after the long-term trends in the V- and R-band datasets were removed by subtracting a third order polynomial fit, two different frequency domain techniques were employed: (i) we calculated a Lomb-Scargle (LS) periodogram (Lomb 1976; Scargle 1982) on each dataset, to search for sinusoidal modulations (this periodogram is a modified discrete Fourier transform (DFT), with normalizations that are explicitly constructed for the general case of time sampling, including uneven sampling; see Scargle 1982); (ii)
we constructed a phase dispersion minimisation periodogram (PDM), which works well even for highly non-sinusoidal light curves (see Stellingwerf 1978).

As there are two candidate orbital periods for LMC X–2 (~8.2 h or ~12.5 d), searches were made with optimal ranges and resolution for each period. For the shorter period a frequency space of 1-10 cycle d$^{-1}$ was searched with a resolution of 0.0001 cycle d$^{-1}$, and for the longer period a frequency space of 0.01-1 cycle d$^{-1}$ was searched with the same resolution as above. No significant dips were found in the PDM plots for either V- or R-band. The short periodicity LS periodogram for the V-band data shows one peak that is just above the 99% confidence limit (Fig. 2). This peak corresponds to 2.68 h. However, no significant peaks were found in the LS for the R-band data. Searches were also carried out on the better sampled section of V- and R-band data, with no significant periodicity being found with either method.

By constructing the cumulative probability distribution (CDF) of the random variable $P_X(\omega)$, the power at a given frequency, where $X$ is pure noise (Scargle 1982), we can measure the significance of the peaks in the LS periodogram. A peak power that is above the 99 per cent confidence level read from the CDF for the dataset would indicate that a significant period had been found. In practice the CDF was constructed using a Monte Carlo simulation method. Noise sets with the same sampling as the MACHO data were generated, and the LS periodogram was run upon each one. The peak power occurring in the periodogram due purely to noise was then recorded. This was repeated for ten-thousand noise sets, to produce good statistics. From these values the probability of obtaining a given peak power from pure noise can then be calculated and the CDF derived. In order to test the significance of peaks from a given data set, the generated noise sets should have the same variance. Therefore, each noise set was generated from a random number generator that takes values from a Gaussian distribution with the same variance as the data set.

The V- and R-band data were folded on a value found from the highest peak in the LS periodogram that was within the 3-$\sigma$ measurement error of the ~8.2 h period found by Callanan et al. (1990). The folded light curves were binned, so as to search for evidence of any weak underlying modulation in the light curve (Fig. 3), but no significant modulation is evident. The datasets were then folded and binned using the previously proposed 12.54-d period (Crampton et al. 1990), the resultant light curves were flat within the errors. Finally the V- and R-band data were bin-folded on the most significant peak in the PDM in the region of 12.54 d (note that Crampton et al. 1990 quote no error for their period and their observations only span ~9 d, so we assumed that a significant peak at 14.06 d is relevant), but again no periodic modulation is found (Fig. 3).

To set limits for the detection of each of the candidate periods in the V- and R-band datasets, the above CDF technique was repeated using the real data as the input to the Monte-Carlo simulations, but also adding a sinusoidal signal with given semi-amplitude and period. The CDF was calculated using an appropriate range and resolution for both the 8.15 h and the 12.54 d periods. The period for the sinusoid was fixed at the quoted value and the CDF calculation was repeated for varying values of the amplitude.

The upper limit for detection of a 12.5 d periodicity in the V-band data at 99 per cent confidence is 9.9 per cent flux modulation semi-amplitude, and in the R-band data is 8.1 per cent. For an 8.2 h periodicity, the upper limit for detection at 99 per cent confidence in the V-band data is 11.1 per cent flux modulation semi-amplitude, and 9.3 per cent for the R-band data.

The failure to find a period around 8.2 h may be due to the sampling of the MACHO data, which was not optimised for finding short periodicities at the low semi-amplitude found previously (note the higher noise levels in Fig. 2 (top left) and (bottom left) compared to Fig. 2 (top right) and (bottom right)).

The 12.54-d modulation was previously found with a semi-amplitude of 0.5 mag, a factor of 5 above our detection limit; if it was present in the MACHO data it should have been found.

4 ESO V-BAND LIGHT CURVE

LMC X–2 was also observed with the ESO 0.91-m Danish telescope at La Silla between 1997 November 17 - December 12 in order to further investigate the 12.54-d periodicity found by Crampton et al. (1990). Using a Tek CCD, V-band photometry was obtained with integration times of 300 s. Individual CCD frames were trimmed, corrected for bias, and flattened using the IRAF reduction routine CCDPROC. Point spread function (PSF) fitting was performed with the IRAF implementation of DAOPHOT II (Stetson 1987). Magnitudes of LMC X–2 were determined using two standard stars of similar colour.

The light curve obtained (Fig. 4) shows that the variation of ~0.5 mag seen by Crampton et al. (1990) is present at our day 7, but it is not repeated 12.54 d later. A dip of ~0.25 mag also occurs at day 13.5, and the source is declining at day 25. This suggests that the dipping is intrinsic to the source and the variations are not modulated on a 12.54-d period. The source appears brighter compared to the observations taken by Crampton et al. (1990), but this may be due to an overall brightening of the source as is also seen in the MACHO light curve after day 1800 (Fig. 1).
5 DISCUSSION

The results from the MACHO data and the ESO light curve indicate that the orbital period of LMC X–2 is not 12.54-d. There is however evidence of non-periodic variations on time-scales of ~tens of days which would explain the results found by Crampton et al. (1990). Long term variations occur in other LMXBs (cf Cyg X–2; Smale & Lochner 1992; Wijnands, Kuulkers & Smale 1996) which are not associated with the orbital period of the system. In high mass X-ray binaries (HMXB) super-orbital periods are known for several sources. Theories to explain these long term variations include precession of a tilted accretion disc, precession of the neutron star, mass transfer feedback and triple systems (see Priedhorsky & Holt 1987 and Schwarzenberg-Czerny 1992). In LMXBs such superorbital periods are much less common. It is thought that they may be due to radiation-driven warped accretion discs (e.g. Wijers & Pringle 1999) or a disc instability in the system (Priedhorsky & Holt 1987).

The light curves from the MACHO and ESO data do not confirm the 8.2-h period for LMC X–2 found by Callanan et al. (1990). However, had this periodicity been present at the Callanan et al. (1990) amplitude we could not have detected it (as it is below our upper limit) and so this modulation still awaits confirmation.

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Figure 1: The optical light curves in blue (top) and red filters (bottom) of LMC X–2 from MACHO project observations. The $V$ and $R$ magnitudes have been calculated using the absolute calibrations of the MACHO fields. Time zero corresponds to 02 Jan 1992 UT 00:00.
Figure 2: Results of applying different period searching techniques to our LMC X–2 MACHO V-band light curve. A phase dispersion minimisation analysis of shorter periods (frequency space of 1-10 cycle d$^{-1}$) (top left) and longer periods (frequency space of 0.01-1 cycle d$^{-1}$) (top right) were searched with a resolution of 0.0001 cycle d$^{-1}$. Lomb-Scargle periodogram for shorter periods (bottom left) and longer periods (frequency space and resolution as above) (bottom right).
Figure 3: MACHO photometry of LMC X–2 folded in 20 phase bins on (a) 8.14 h (b) 14.06 d for both V-band (i) and R-band (ii). Error bars for all binned light curves are the standard errors for the data points in each bin.
Figure 4: ESO V-band light curve (300 s integrations) of LMC X-2 (top) and a star of comparable brightness (bottom).