J. Astrophys. Astr. (2002) **23,** 33–38

Superorbital Period Variations in the X-ray Pulsar LMC X-4

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Abstract. We report the discovery of a decay in the superorbital period of the binary X-ray pulsar LMC X-4. Combining archival data and published long term X-ray light curves, we have found a decay in the third period in this system ($P \sim 30.3$ day, $\dot{P} \sim -2 \times 10^{-5}$ s s^{-1}). Along with this result, a comparison of the superorbital intensity variations in LMC X-4, Her X-1 and SMC X-1 is also presented.

Key words. Accretion, accretion disks—stars: individual (LMC X-4)—stars: neutron—X-rays: stars, binaries.

1. Introduction

Apart from the binary period, long-term periodic intensity variations are known to be present in many X-ray binaries. There are four X-ray binaries in which the presence of long periods is very well established. These are

(1) Her X-1 (a 1.7 d binary with a 35 d long third period, Giacconi *et al.* 1973),
(2) LMC X-4, (1.4 d and 30.5 d, Lang *et al.* 1981),
(3) SMC X-1, (3.9 d and 60 d, Wojdowski *et al.* 1998) and
(4) SS433, (13.1 d and 164 d, Margon 1984).

The first three of these, Her X-1, LMC X-4 and SMC X-1 are also accreting X-ray pulsars with pulse periods of 1.24, 13.5 and 0.75 s respectively. Superorbital periods in Her X-1, LMC X-4, and SS 433 are most stable and are believed to be produced by the precession of the accretion disks. The mechanisms proposed to cause the precession of the disks are

(1) forced precession of a tilted disk by the gravitational field of the companion star (Katz 1973) and
(2) precession of a disk that is slaved to a misaligned companion star (Roberts 1974).

Some excursions in the superorbital periods are known to be present in Her X-1 (Ögelman 1985) and SS 433 (Margon 1984). We report here detection of the same in LMC X-4.

2. Analysis and results

2.1 *Period analysis*

The superorbital period of LMC X-4 was discovered by Lang *et al.* (1981) using the HEAO-A1 scanning modulation colimator. They reported a period of 30.48 ± 0.06 day and the time of arrival of the rising edge was 2443371.0 ± 1.0 (JD). We have used the long term light curves of LMC X-4 obtained with the All Sky Monitors (ASM) of the GINGA and RXTE satellites and applied the Lomb and Scargle method to search for periodicities. The GINGA-ASM light curve resulted in a superorbital period of 30.17 $\pm$ 0.08 day with the time of arrival of the rising edge 2446836.0 ± 2.0 (JD) while the same obtained with the RXTE-ASM are 30.296 ± 0.014 day and 2450070.0 ± 1.0 (JD) respectively. The superorbital intensity variation profiles obtained by folding the light curves at the respective long periods are shown in Fig. 1.

The superorbital period of LMC X-4 obtained with GINGA-ASM and RXTE-ASM light curves is smaller than that obtained from the HEAO-A1 observations. The decrease in superorbital period over this time span corresponds to a period derivative of $-1.8 \pm 0.8 \times 10^{-5}$ s s^{-1} or a decoherence time scale of $\sim$ 20 years. The RXTE-ASM observations span about five years, which may cause considerable decoherence in the superorbital phase. We have, therefore, carried out a more detailed pulsation analysis allowing for a period derivative. The pulse folding and χ^2 maximising method was applied with a period derivative, and the same was done for 400 different period derivatives. From each trial, the maximum χ^2 and the corresponding long period was selected. The resulting distribution of maximum χ^2 against the respective period derivatives is shown in the left panel of Fig. 2. The maximum of this χ^2 distribution occurs corresponding to a period derivative of $-2.1 \pm 0.1 \times 10^{-5}$ s s^{-1}, obtained by fitting a gaussian profile near the maximum (shown in the inset). This is similar to the long term derivative of the superorbital period obtained by fitting a straight line to the three periods described above.

2.2 *Arrival time analysis*

Arrival time of the rising edge of the superorbital intensity variation is available for HEAO-A1 (Lang *et al.* 1981). We therefore determined the same from the GINGA-ASM and RXTE-ASM light curves. LMC X-4 was observed many times with the Medium Energy (ME) detectors of EXOSAT. Though the combined EXOSAT-ME light curves cannot be used for an independent determination of the superorbital period, we have determined the arrival time (2445620.0 ± 3.0 JD) by folding the light curve. The superorbital periods obtained from the HEAO-A1, GINGA-ASM and RXTE-ASM at the respective epochs were fitted with a straight line and an approximate value for the same during the EXOSAT-ME observations was calculated by interpolation. The EXOSAT-ME light curve has poor coverage in the rising part of the light curve (see right panel of Fig. 1), and therefore we associate a larger error with this arrival time. There is some ambiguity in the number of cycles between the GINGA and RXTE observations. Two superorbital phase connected solutions are obtained with different number of cycles between the GINGA and RXTE data. Residuals of the arrival times after fitting a straight line to these solutions are shown in Fig. 2(b) with data points marked as squares and circles respectively. The first solution has small residuals, but

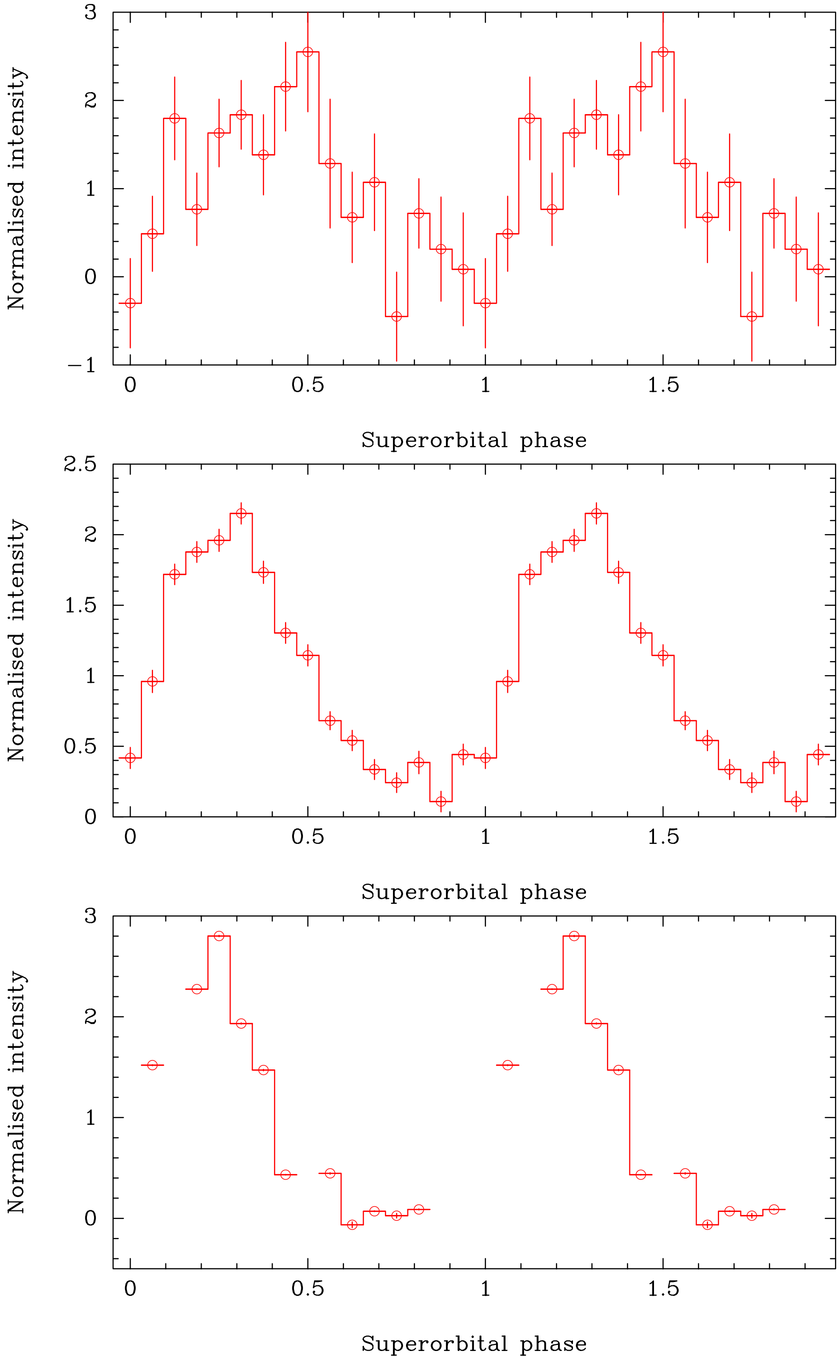

Figure 1. The profiles of superorbital intensity variations of LMC X-4 obtained from GINGA-ASM, RXTE-ASM and EXOSAT-ME light curves are shown from top to bottom. See text for details about the superorbital periods obtained/adopted for each data set.

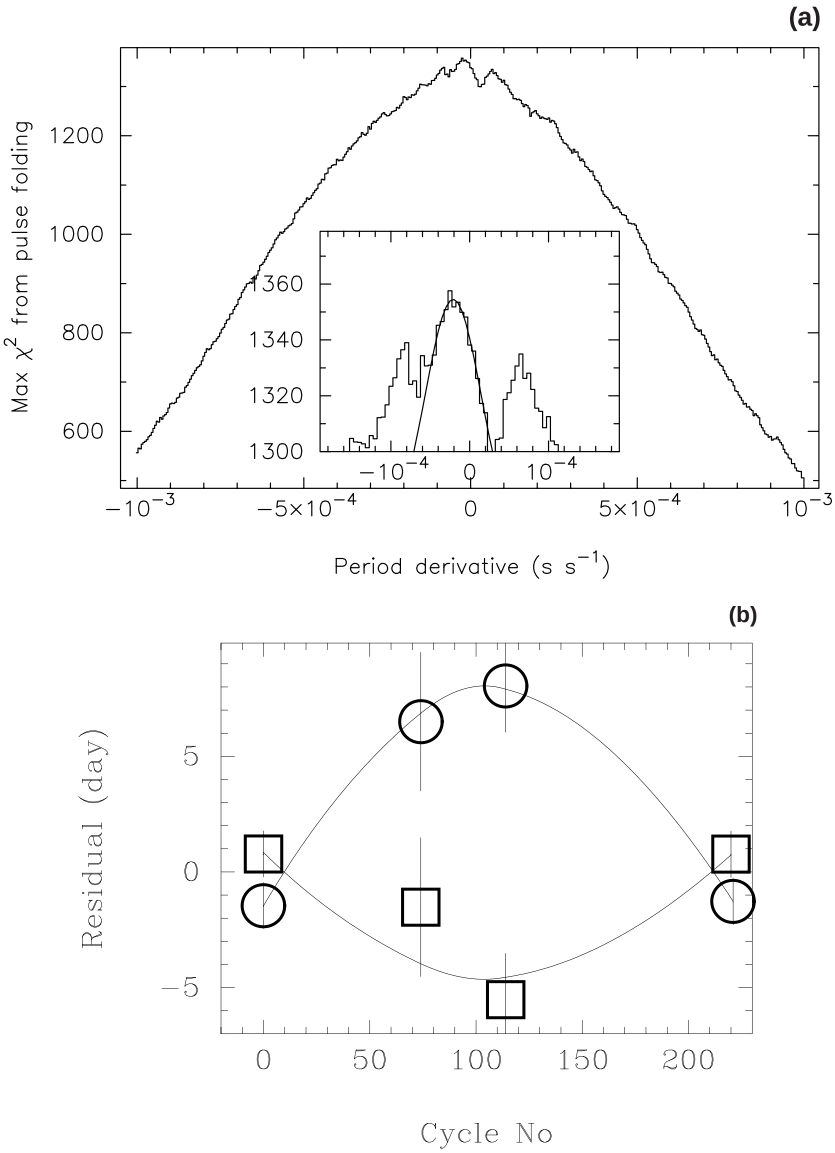

Figure 2. **(a)** The distribution of maximum χ^2 against the respective period derivatives obtained from the RXTE-ASM light curve is shown here. See text for details. The best fit gaussian profile near the maximum is shown in the inset. **(b)** Residuals of the arrival times after fitting a straight line to the arrival time data. An ambiguity in the number of cycles between the GINGA and RXTE observations results in two solutions presented with circles and stars in this figure. The lines represent the best fit quadratic solutions to the arrival time data.

the present superorbital period is required to be 30.45 day, which can be ruled out from RXTE-ASM data alone. The second solution requires a period of 30.31 d, close to the value obtained with the RXTE-ASM light curve. The second solution gives large residuals for the GINGA and EXOSAT arrival times. To account for the residuals, we introduced a period derivative and fitted a quadratic function to the arrival times.

With this, the two solutions require initial periods of 30.35 day and 30.48 day and period derivatives of $(3 \pm 2) \times 10^{-5}$ s s^{-1} and $(-5 \pm 2) \times 10^{-5}$ s s^{-1} respectively. The second solution is in rough agreement with the superorbital period and period derivative obtained from the RXTE-ASM light curve alone. We take this to be the correct representation of the long term evolution of LMC X-4 superorbital period.

3. Discussion

In the present work, we report detection of superorbital intensity variations in LMC X-4 with EXOSAT-ME, GINGA-ASM and RXTE-ASM detectors. These measurements, when combined with the first detection of long period with HEAO A-1 (Lang *et al.* 1981), indicates a decay in the superorbital period of LMC X-4. We have applied three different techniques,

(1) period measurements from individual data sets,
(2) χ^2 maximisation by varying $\dot{P}$ with the RXTE-ASM data and
(3) arrival time analysis.

The results obtained from these analyses are consistent and indicate a long period derivative of about -2×10^{-5} s s^{-1}.

As mentioned earlier, superorbital periodic intensity variations have been observed in many X-ray binaries. However, there is strong difference in the way these intensity variations take place even in the subclass of accreting binary X-ray pulsars. While the superorbital intensity variations in LMC X-4 is coherent, in Her X-1 it has short term variations because it is synchronized with the binary cycle and switch-over to the high state takes place at specific orbital phases (Boynton *et al.* 1980, Scott and Leahy 1999). During anomalous low states in Her X-1, which can last for a few months, a change in the length or phase of the superorbital period is noticed (Oosterbroek *et al.* 2001). On the other hand, the superorbital intensity variations in SMC X-1 is quasi-periodic with recurrence times that wander between 50 and 60 days (Wojdowski *et al.* 1998).

In either case of forced precession or a slaved disk model, the period of precession is linked with the orbital period of the binary. Recently, Levine *et al.* (2000) reported a firm detection of orbital period decay in LMC X-4. In the precessing accretion disk model, it is therefore possible that the changing binary parameters cause the decay in the superorbital period in LMC X-4.

Acknowledgement

This research has made use of data obtained through the HEASARC Online Service, provided by the NASA/GSFC. We also thank the RXTE-ASM and GINGA-ASM teams for providing the valuable data.

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