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# ON THE COMPLEX VARIABILITY OF THE SUPERORBITAL MODULATION PERIOD OF LMC X-4

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## ABSTRACT

LMC X-4 is an eclipsing high-mass X-ray binary exhibiting a superorbital modulation with a period of $\sim 30.5$ days. We present a detailed study of the variations of the superorbital modulation period with a time baseline of $\sim 18$ years. The period determined in the light curve collected by the Monitor of All-sky X-ray Image (MAXI) significantly deviates from that observed by the All Sky Monitor (ASM) onboard the Rossi X-ray Timing Explorer (RXTE). Using the data collected by RXTE/ASM, MAXI, and the Burst Alert Telescope (BAT) onboard Swift, we found a significant period derivative, $\dot{P} = (2.08 \pm 0.12) \times 10^{-5}$. Furthermore, the O–C residual shows complex short-term variations indicating that the superorbital modulation of LMC X-4 exhibits complicated unstable behaviors. In addition, we used archive data collected by the Proportional Counter Array (PCA) on RXTE to estimate the orbital and spin parameters. The detected pulse frequencies obtained in small time segments were fitted with a circular orbital Doppler shift model. In addition to orbital parameters and spin frequency for each observation, we found a spin frequency derivative of $\dot{\nu} = (6.482 \pm 0.011) \times 10^{-13}$ Hz $\cdot$ s$^{-1}$. More precise orbital and spin parameters will be evaluated by the pulse arrival time delay technique in the future.

*Key words:* X-ray binary: superorbital modulation: LMC X-4

## 1. INTRODUCTION

The eclipsing high mass X-ray binary LMC X-4 consists of a 1.25 $M_\odot$ neutron star and a 1.45 $M_\odot$ mass donor (Kelley et al. 1983; van der Meer et al. 2007). The spin period of the neutron star is $\sim 13.5$ s and the binary orbital period is $\sim 1.4$ d (White 1978). This system also shows periodic superorbital modulation with a period of $\sim 30.5$ d in its X-ray light curve (Lang et al. 1981) caused by a precessing accretion disk with mode 0 stable warp that obscures the X-ray emission from the neutron star (Ogilvie & Dubus 2001; Clarkson et al. 2003). Using the light curve collected by the All-Sky Monitor (ASM) onboard the Rossi X-ray Timing Explorer (RXTE), as well as the arrival time analysis from both the GINGA and RXTE ASM data, Paul & Kitamoto (2002) found a time derivative of the superorbital period with a value of $\dot{P} = -2 \times 10^{-5}$ s $\cdot$ s$^{-1}$. However, the arrival time also provides another possible $\dot{P}$ value of $3 \times 10^{-5}$ s $\cdot$ s$^{-1}$ because the large observational gap between GINGA and RXTE observations would probably cause a cycle count ambiguity. The RXTE collected a huge amount of usable data up to 2010, and two new-generation projects, the Burst Alert Telescope (BAT) onboard Swift and the Monitor of All-sky X-ray Image (MAXI), have taken over the monitor mission of RXTE. Therefore, we can further study the long-term variability of the superorbital modulation of LMC X-4 in detail. Furthermore, LMC X-4 is a pulsar whose orbital and spin parameters can be precisely measured. In this paper, we also present our preliminary analysis results for evaluation of orbital and spin parameters using the orbital Doppler shift technique.

## 2. OBSERVATIONS

- `RXTE ASM & PCA`

Launched in late 1995, the ASM continuously swept the entire sky every 90 minutes, in an energy range of 1.3 to 12.1 keV. The data collected from 1996 to 2010 were used in this research. To measure the orbital and spin parameters, we used data collected by the Proportional Counter Array (PCA). Only events within the energy range of 8 to 20 keV were adopted to enhance the pulsation.

- `Swift BAT`

The Swift observatory was launched in 2004 and is continues observations now. The BAT onboard Swift provides monitoring light curves with a time resolution of 90 minutes and an energy range of 15 – 150 keV.

- `MAXI`

MAXI is an X-ray monitoring camera onboard the International Space Station. The MAXI team has

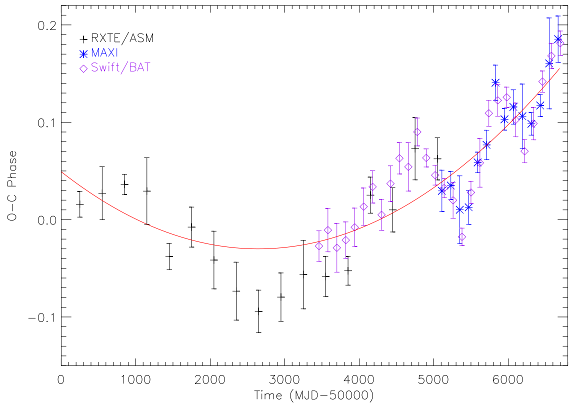


**Figure 1.** The O–C result for the evolution of superorbital modulation.

archived light curves with time resolution of 90 minutes from MJD 53418. The energy range of MAXI is 2 – 20 keV.

All the data were barycenter corrected using the ftools task `earth2sun`. Combining these three observatories, the time baseline in this research is $\sim$ 6700 days.

## 3. RESULTS

### 3.1. The Lomb-Scargle Periodograms

We first applied the Lomb-Scargle algorithm on all the three data sets to examine the superorbital modulation period in these observations. The period detected in the RXTE ASM data set is $P = 30.3227 \pm 0.0030$ days. On the other hand, the periodicities detected in Swift BAT and MAXI data sets are $P = 30.3668 \pm 0.0019$ days and $P = 30.4034 \pm 0.0057$ days, respectively. These periods significantly deviate from each other.

### 3.2. The Long-Term Evolution of the Superorbital Modulation

We then used the O–C analysis technique to trace the long-term evolution of the superorbital modulation period of LMC X-4. We first create a linear ephemeris based on the period determined using the RXTE ASM light curve. Then, we divided the light curves into several segments with an appropriate window size. The data points in individual segments were folded according to the linear ephemeris. We fitted the superorbital profiles in individual segments with Gaussian functions to obtain the maxima points, which are set to be the fiducial points.

The phase evolution of the superorbital modulation is shown in Fig. 1. We fitted the data points using a quadratic curve and established a quadratic ephemeris as: $T_{max} = MJD(50169.5 \pm 0.28) + (30.2642 \pm 0.0047) \times N + (3.15 \pm 0.19) \times 10^{-4} \times N^2$ where the period derivative is $\dot{P} = (2.08 \pm 0.12) \times 10^{-5}$ s $\cdot$ s$^{-1}$. Furthermore, the $\chi^2_\nu$ of the quadratic fitting is 9.22, which indicates a poor fitting. From the evolutionary track, we noticed that the superorbital modulation period of LMC X-4 also has short-term variability.

Table 1
THE ORBITAL AND SPIN PARAMETERS OF FITTED RESULT BY AN ORBITAL DOPPLER SHIFT MODEL

| | $\nu_0$ [Hz] | $P_{orb}$ [day] | $a\sin(i)$ [lt-s] | $T_{\pi/2}$ [MJD] |
|---|---|---|---|---|
| 1996 | 0.074020(10) | 1.17(11) | 18.4(30) | 50315.207(51) |
| 1998 | 0.074065(51) | 1.394(11) | 22.3(17) | 51110.833(24) |
| 1999 | 0.074088(10) | 1.244(74) | 24.9(35) | 51532.019(45) |

### 3.3. The Orbital Parameters

We further used the archive data collected by PCA equipped on RXTE to evaluate the orbital and spin parameters. First, we divided the data into small segments with time span of 1000 s to 3000 s for each, as the detected spin variation due to orbital motion can be neglected over such a small time interval. Secondly, only data segments that were observed in the superorbital high state (phase between 0.8 and 1.2) and out of the eclipsing region (i.e., outside the orbital phase -0.1 to 0.1) whose phase is evaluated by the ephemeris proposed by Levine et al (2000) were included. Thus, three observations observed in 1996, 1998 and 1999 were used for further analysis.

After the data selection, we adopted the z-test to search for periodicity in each segment. The unweighted peak frequencies from the power spectra were fitted with a circular orbital Doppler shift model for each observation. The fitting results for the three observations are listed in Table 1. The orbital period can be obtained using the O–C method applied on $T_{\pi/2}$, which gives a mean orbital period of $P_{orb} = 1.40833(12)$ d. On the other hand, we found the spin frequencies of these three observations have significant drift. A frequency derivative of $\dot{\nu} = (6.482 \pm 0.011) \times 10^{-13}$ Hz $\cdot$ s$^{-1}$ was obtain by fitting the spin frequencies with a linear function.

## 4. SUMMARY & FUTURE WORK

Using the all-sky monitoring data collected by RXTE ASM, Swift BAT, and MAXI, we find that the superorbital modulation period of LMC X-4 is unstable. The O–C result shows that it contains not only a significant period derivative but also short-term variability. However, the mechanism is still unknown. If the superorbital modulation period is caused by the radiation induced warp of the accretion disk, the relationship between the flux and modulation period should be further examined. Furthermore, the relationship between spin, orbital, and superorbital modulation is also worth further study. In addition, using the data collected by PCA/RXTE, we evaluated the orbital and spin parameters. These parameters will be more precisely determined using the pulse arrival time delay technique.

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