Near-periodical spin period evolution in the binary system LMC X-4

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ABSTRACT

In this paper we investigated the long-term evolution of the pulse-period in the high-mass X-ray binary LMC X-4 by taking advantage of more than 43 yrs of measurements in the X-ray domain. Our analysis revealed for the first time that the source is displaying near-periodical variations of its spin period on a time scale of roughly 6.8 yrs, making LMC X-4 one of the known binary systems showing remarkable long term spin torque reversals. We discuss different scenarios to interpret the origin of these torque reversals.

Key words: accretion, accretion discs – stars: individual: LMC X-4 – X-rays: binaries.

1 INTRODUCTION

The High-Mass X-ray Binary (HMXB) LMC X-4 has been observed in the X-ray domain, as well as in other energy domains, since more than forty three years. It was originally discovered by the Uhuru satellite (Giacconi et al. 1972) and it is known to be located in the Large Magellanic Cloud (LMC) at a distance of $\sim 50$ kpc. Based on the analysis of the very deep objective-prism plates Sanduleak and Philip (1976) proposed that the optical counterpart of LMC X-4 is an OB star, showing optical flux modulations on the time scale of $\sim 1.4$ days presumably connected with the orbital motion in the binary system (Chevalier and Ilovaisky 1977; Hutchings et al. 1978). Regular X-ray eclipses occurring on the same periodicity were detected later in the X-ray lightcurve of the source with the instruments onboard the SAS-3 and Ariel V observatories (Li et al. 1978; White 1978), finally confirming the binary nature of the source. The orbital parameters of the system were investigated in a number of papers (see, e.g., Levine et al. 1991; Safi-Harb et al. 1996; Woo et al. 1996; Levine et al. 2000; Naik & Paul 2004, and references therein) and refined more recently by Falanga et al. (2015) and Molkov et al. (2015).

LMC X-4 is also known to display a super-orbital modulation in the X-ray domain with a period of $P_{\text{sup}} \sim 30.5$ days, reported for the first time by Lang et al. (1981) using data from the HEAO1 observatory. The dynamic range in the X-ray luminosity displayed by the source over the period of the super-orbital modulation (oscillating between high and low emission states) is of about two orders of magnitude, reaching up to $(4 - 5) \times 10^{38}$ erg s$^{-1}$ (see, e.g. Woo et al. 1996; Heemskerk & van Paradijs 1989; Tsygankov & Lutovinov 2005; Grebenev et al. 2013).

One of the most widely accepted mechanisms to produce such modulation foresees the presence of a precessing warped accretion disk around the compact object in the binary system, which periodically obscures the source of the X-ray radiation (see, e.g., Ogilvie & Dubus 2001; Clarkson et al. 2003; Kotze & Charles 2012, and references therein). Such scenario has also been applied to the case of LMC X-4 in many papers which investigated the long term evolution of the X-ray emission of the system (see, e.g., Paul & Kitamoto 2002; Clarkson et al. 2003; Tsygankov & Lutovinov 2005; Molkov et al. 2015). The same super-orbital modulation was also long known to be present in the optical waveband (Ilovaisky et al. 1984; Heemskerk & van Paradijs 1989).

LMC X-4 shows also sporadic large X-ray flares which have a typical duration from tens of minutes up to few hours and occur unpredictably once every few days. During these events the X-ray luminosity of the source can increase up to an order of magnitude (Epstein et al. 1977; Pietsch et al. 1985; Levine et al. 2000; Moon et al. 2003; Tsygankov & Lutovinov 2005). The physical mechanism triggering these flares is still poorly understood, but it is probably related to temporarily variations in the mass accretion rate onto the compact object (Levine et al. 2000).

The presence of an X-ray pulsar in LMC X-4, spinning at $P \simeq 13.5$ s was revealed with the SAS-3 observatory

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during a series of X-ray flares occurred between 1975-1976 (Kelley et al. 1983). This led to the association of LMC X-4 with the class of the so-called accretion powered X-ray pulsars (APXPs). Many sources in this class are known to display spin-up episodes, during which the spin period of the neutron star decreases, and episodes of spin-down, when the rotation of the neutron star is slowed down probably due to the accretion torques and the interactions between the compact object magnetosphere and the surrounding accretion disk. Depending on the different systems, the spin-up and spin-down episodes can last from days to weeks, extending up to several years in the most extreme cases (see, e.g., reviews of Nagase 1989; Lutovinov et al. 1994; Bildsten et al. 1997; Lutovinov & Tsygankov 2009).

In this paper, we use all historical spin period measurements of the neutron star hosted in LMCX-4 in order to investigate for the first time the long-term trends in its variations over the past ~43 yrs. A description of all the historical measurements is provided in Sect. 2, together with the summary of all new determinations of the source spin period obtained with the most recently available data. We have made use in this paper of data from twelve different observatories and most of their on-board instruments. In several cases, the measurements of the source spin period were taken directly from the literature, while in many others we reanalyzed the data to improve previous results. A summary of all our findings is reported in Sect. 3. We discuss all the results in Sect. 4.

2 DATA SETS ON LMCX-4

All measurements of the spin period of the neutron star hosted in LMCX-4 available to date and used in this paper are summarized in Table 1, together with the corresponding uncertainties. We illustrated in all the following sub-sections how the different measurements have been obtained. Note that the uncertainties on the spin period values obtained by us and not retrieved in the literature were estimated by using the technique described in Boldin et al. (2013). For each observation, we generated a set of $10^4$ synthetic lightcurves in which the count-rate of the source was randomly varied in each time bin within the 1σ confidence level of the original measurement. We used the mean value of the pulse period distribution obtained from the synthetic lightcurves as the best value of the source spin period and the standard deviation of the same distribution as the associated 1σ uncertainty.

2.1 SAS-3

The third US Small Astronomy Satellite (SAS-3) observed LMCX-4 in two occasions: during 6 days in February 1976 with the Rotating Modulation Collimators (ROMC operating in the 2-11 keV energy band; Dobrzycki et al. 1976) and during 1.5 days in May 1977 with the Y-axis detectors (operating in the 6-12 keV energy band; Lewin et al. 1976). A total of five flaring episodes (three in 1976 and two in 1977) were detected during these observations. X-ray pulsations were registered only during these events. All details of the data analysis and pulse period measurements are given in

Table 1. Log of all LMCX-4 pulse-period measurements used in the present work.

| Date MJD | Period (s)   | Observatory | Reference |
|----------|--------------|-------------|-----------|
| 42831.43 | 13.528(2)    | SAS-3       | Kelley et al. (1983) |
| 43286.67 | 13.525(7)    | SAS-3       | Kelley et al. (1983) |
| 44589.60 | 13.5113(40)b | Einstein     | Naranan et al. (1985) |
| 45666.0d | 13.5019(2)   | EXOSAT      | Pietsch et al. (1985) |
| 47229.331d | 13.459578(9) | Ginga       | Woo et al. (1996) |
| 47741.9904d | 13.49798(1) | Ginga       | Levine et al. (1991) |
| 48558.8598d | 13.50292(2) | ROSAT       | Woo et al. (1996) |
| 49468.6859d | 13.5075(2)  | ASCA        | Paul et al. (2002) |
| 50227.8069d | 13.5085(4)  | RXTE        | this work   |
| 50915.1214d | 13.5068(6)  | RXTE        | this work   |
| 51106.6399d | 13.50260(12)| BeppoSAX    | Naik & Paul (2004) |
| 51109.4574d | 13.5031(3)  | RXTE        | this work   |
| 51531.9844d | 13.4960(4)  | RXTE        | this work   |
| 52892.1c | 13.4959(5)   | XMM-Newton  | this work   |
| 53172.8s | 13.4974(5)   | XMM-Newton  | this work   |
| 54480.5c | 13.5087(2)   | Suzaku      | Hung et al. (2010) |
| 54507.3c | 13.5091(1)   | Suzaku      | Hung et al. (2010) |
| 54561.7s | 13.5060(6)   | Suzaku      | Hung et al. (2010) |
| 56112.8s | 13.49892(3)  | NuSTAR      | Shitykovsky et al. (2016) |
| 56906.58a | 13.490(8)    | XRT/Swift   | this work   |

$^a$ Pulsations have been detected only during flaring activity
$^b$ The value has been corrected in this work, see text for details
$^c$ Approximate middle time of the observation
$^d$ Epoch of the mid-eclipse obtained from the fit to the data
Kelley et al. (1983). We quote in Table 1 the relevant values from the above paper.

2.2 HEAO-2

LMC X-4 was in the field of view of HEAO-2, the second High Energy Astrophysical Observatory (Einstein, Giacconi et al. 1979), several times during the mission lifetime (from November 1978 to April 1981). The analysis of these data and the corresponding results were reported in Naranan et al. (1985). Pulsations from the source were significantly detected only during the X-ray flares occurred on December 16, 1980 (MJD 44589.6). In that occasion, the measured apparent spin period was 13.530 ± 0.004 s (not corrected for the orbital motion). In order to derive the corrected period we used the orbital ephemerides published by Kelley et al. (1983) and obtained the intrinsic period of the neutron star rotation for the date of the HEAO-2 observations as $P = 13.5113$ s. This value is reported in Table 1. We note that this value does not change significantly if the more updated ephemerides provided by Molkov et al. (2015) are used for the calculation. In this case we obtain $P = 13.5117$ s.

2.3 EXOSAT

Pulsations from LMC X-4 were detected by the European X-ray Observatory Satellite (EXOSAT, Andrews 1984) in five observations carried out in October-November 1983. Note that pulsations were detected not only during the flaring activity of the source but also in its persistent state during the more intense observational monitoring of the source carried out from 1983 November 17 to November 19. The results of this analysis were reported by Pietsch et al. (1985) and included in Table 1.

2.4 Ginga

The Astro-C observatory (Ginga) was the third Japanese X-ray astronomy mission (Matsumoto 1987). The pulsed signal from LMC X-4 was clearly detected during two long observations performed with the Large Area Counter instrument (LAC, Turner et al. 1989) on 1988 March 7-10 (Woo et al. 1996) and 1989 August 3-5 (Levine et al. 1991), when the source was in a high state of its super-orbital cycle. The pulse period values reported in these papers are quoted in Table 1. Note that the data collected during the source X-ray flares occurred in the two observations were excluded from the analysis.

2.5 ROSAT

Observations of LMC X-4 were performed with the Position Sensitive Proportional Counter (PSPC, Pfeffermann et al. 1987) on-board the Roentgen Satellite ROSAT (Trümper 1983) starting from 1991 October 28 to November 3. Details of the extraction and timing analysis of the source lightcurves in the 0.1 – 2.5 keV energy range are given in Woo et al. (1996). In Table 1 we quote the source pulse period value reported in this paper. Also in this case, the data used to determine the spin period did not include any flaring episode.

2.6 ASCA

The Advanced Satellite for Cosmology and Astrophysics (ASCA, Tanaka et al. 1994), observed LMC X-4 on three occasions: 1994 April 26-27, 1995 November 24-25, and 1996 May 24-25. During all observations the source was in its high super-orbital state and no flares were detected. For the timing analysis only the first and the third observations were used, as during the second one the source was caught in eclipse. A first estimate of the pulse period obtained from these two observations was reported by Vrtilek et al. (1997). These authors showed that the source pulse period was 13.5069 ± 0.0007 in 1994 and 13.5090 ± 0.0002 in 1996. These values were later improved by Paul et al. (2002) and we thus used these updated results in Table 1.

2.7 BeppoSAX

LMC X-4 was observed twice with the Italian-Dutch mission BeppoSAX (see, e.g., Piro et al. 1995, and references therein) during the 6 years of its scientific operations. Only in one of two observations (on 1988 October 20-22) the source was caught in the high super-orbital state and X-ray pulsations were recorded. All details of the BeppoSAX data analysis and the measured value of the pulse period were reported by Naik & Paul (2004). No X-ray flares were observed in the BeppoSAX observations of LMC X-4.

2.8 RXTE

LMC X-4 was observed with the instruments on-board the Rossi X-ray Timing Explorer (RXTE, Bradt et al. 1993) several times during the mission lifetime. In order to measure the source pulse period with a reasonable accuracy, we only made use of the RXTE data which closely covered a number of contiguous binary orbits. These sub-set of the RXTE data comprised anyway several dozens of data segments with a typical duration of few ks.

We considered for our timing analysis only data from the Proportional Counter Array (PCA, Jahoda et al. 2006) collected in different event-modes. We corrected the on-board arrival time of each X-ray event to the rest frame of the Solar System and filtered out events with an energy below 9 keV and above 20 keV. In the 9-20 keV energy band the pulse profile of LMC X-4 is known to be characterized by a simpler shape (see, e.g., Levine et al. 2000), thus making it easier and more reliable to carry out a pulse period search. The data containing eclipses and strong X-ray flares were used in this analysis.

Table 2. Log of all RXTE observations used in this work.

| Series | Dates (MJD) | Total exposure (ks) | Num. of segments |
|--------|-------------|---------------------|-----------------|
| 1      | 50314.6 – 50316.1 | ~ 60 | 17 |
| 2      | 50740.3 – 50749.0 | ~ 31 | 12 |
| 3      | 51106.0 – 51114.5 | ~ 128 | 46 |
| 4      | 51531.5 – 51533.2 | ~ 98 | 20 |

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excluded from the analysis, resulting in a total of four series of PCA observations, as indicated in Table 2. We used the efsearch tool within the FTOOLS software package to determine the apparent source pulse period in each of the PCA observations. The intrinsic pulse period was then calculated by applying the appropriate corrections with the updated binary orbit parameters (Levine et al. 2000).

2.9 XMM-Newton

We have used also data collected with the EPIC-pn and EPIC-MOS instruments (Strüder et al. 2001; Turner et al. 2001) on-board the XMM-Newton observatory (Jansen et al. 2001) during two observations of LMC X-4. The first one was carried out on 2003 September 9-10 for a total exposure time of ∼ 113 ks. The second observation was performed on 2004 June 16 and provided a total exposure time of ∼ 43 ks. All XMM-Newton data were reduced and analyzed by using the Science Analysis System (SAS) version 15.0.0. During both observations LMC X-4 was in a high (bright) state and clearly detected by the EPIC cameras. Strong X-ray flares were registered during the first observation, and two whole X-ray eclipses were detected in both the first and the second data-set. In order to optimize the estimate of the source pulse period, we excluded from our analysis all time intervals corresponding to the flares and eclipses. As the orbital parameters of LMC X-4 could not be independently determined from the XMM-Newton data, we used the binary ephemerides reported by Molkov et al. (2015) in order to correct the on-board arrival time of each XMM-Newton X-ray event. The values of the source spin period we obtained from both observations with the efsearch procedure are reported in Table 1.

2.10 Suzaku

Suzaku (Astro-E2) is the fifth Japanese X-ray astronomy mission (Mitsuda et al. 2007). Three pointed observations of LMCX-4 were carried out in 2008 (January 15, February 11, and April 5). Details of the timing analysis are given in Hung et al. (2010). As it is not possible to independently determine the source orbital parameters by using solely the Suzaku data, these authors measured the pulse period by applying the efsearch technique to the instrumental lightcurves corrected for the binary motion using the ephemerides from Levine et al. (2000). The source pulse periods derived from the three observations are reported in Table 1.

2.11 NuSTAR

The Nuclear Spectroscopic Telescope Array (NuSTAR) mission is the first focusing high-energy X-ray telescope in orbit (Harrison et al. 2013). NuSTAR is endowed with two co-aligned hard X-ray telescopes (the FPMA and the FPMB) that operate in the energy band 3–79 keV. So far, NuSTAR performed an observation of LMCX-4 on 2012 July 4. The total available exposure time is ∼ 40 ks. During the observation the source was caught in the high super-orbital state and no flaring activity was detected. The source lightcurves were obtained from both the FPMA and FPMB modules using a circular extraction region with the radius of 1′ centered on the best known position of LMC X-4. The arrival times of the X-ray photons in both lightcurves were corrected for the Solar System Barycenter and the binary system motion using the ephemerides from Molkov et al. (2015). The source intrinsic pulse period was determined from these data as 13.49892(3) s. A more detailed description of the NuSTAR data analysis, as well as the results of the spectral analysis, can be found in Shtykovsky et al. (2016).

2.12 Swift/XRT

The medium-size mission Swift is conducting scientific observations in the X-ray domain since 2004 (Gehrels et al. 2004). In our analysis we used data collected by the X-ray Telescope (XRT, see Burrows et al. 2005), operating in the 0.2–10 keV energy band. Our group requested several observations of LMC X-4 during the week spanning from 2014 December 3 to 9. The observational campaign consists of a few tens of pointing, reaching a total effective exposure time of about 30 ks. The source was observed during one of its super-orbital high state and significantly detected in each pointing (excluding two of them that caught the source during the X-ray eclipse). One flaring episode lasting about 15 minutes was detected during the XRT campaign. All XRT data used in this paper were carried out in Windowed Timing (WT) mode. We excluded from the analysis the time intervals corresponding to the eclipse and the flaring period. The time arrival of all photons collected by XRT were corrected to the Solar System Barycenter before performing any further analysis. The statistics of the XRT data turned out to be too low to determine the source spin frequency during.
3 RESULTS

The pulse period history of LMC X-4 based on all available data mentioned in the different sub-sections above (from Sect. 2.1 to 2.12) is presented in Fig. 1. This evolution shows an intriguing cyclical behaviour with torque reversals occurring roughly every $P_t \sim 2500$ days (i.e. $\sim 6.8$ years). As there is not yet a clear understanding on the mechanism producing torque reversals in HMXBs, we did not attempt to describe the data in Fig. 1 with a physical model, but rather tried to find some simple mathematical functions that could qualitatively match the observational results. Note that the goodness of the match is not formally evaluated through a proper fit, as the available data are too sparse. We limited the present attempt to the identification of key parameters (e.g., the quasi-periodic time-scale of the torque reversals) that can provide some insights into the mechanisms driving the peculiar variability of the timing properties of the source.

In the top panel of Fig. 2 we show the case in which the apparent periodical variability of the spin period of LMC X-4 is tentatively described with the sinusoidal function:

$$P(t) = \overline{P}_{\text{spin}} \left(1 + A \sin \left(2\pi \frac{t - T_0}{P_3}\right)\right).$$

Here $\overline{P}_{\text{spin}}$ is the mean value of the source spin period over the whole observational period (in seconds), $P_3$ is the characteristic timescale of the variability, $T_0$ is the time of phase zero, and $A$ the amplitude of the variability ($t, T_0,$ and $P_3$ are all in units of days).

The equation above describes the data reasonably well, and we obtained $P_3 \approx 5090, A = 5.3 \times 10^{-3}\text{s},$ and $\overline{P} = 13.5021\text{s}$. Only the first two points obtained from the SAS observatory deviate from the qualitative periodical function. It is interesting to note that only these measurements together with the one based on the HEAO-2 data, were obtained during episodes of the source flaring activity. All other spin period values were measured during quieter periods in the high super-orbital phase. It is thus possible that some mechanism is at work during the flares to produce changes in the observed source pulsation period.

As the available observational data (Fig. 1) are rather sparse, we cannot exclude that the different spin-up and spin-down episodes alternate in a more complicated fashion than a simple sinusoidal trend. Therefore we show in the bottom panel of Fig. 2 an another example in which data are described by a sequence of power laws with identical absolute values of the slope but alternated signs:

$$P(t) = P_i - (-1)^i |\dot{P}| (t - T_i), \, i \in [1, 4].$$

In the equation above, $\dot{P}$ is the period derivative, $T_i$ is the time interval preceding $t$ when the pulse-period derivative changes sign, and $P_i$ is the pulse period in the time interval $T_i$ (in the equation all time intervals are expressed in days and all spin period values in seconds). According to this model, the characteristic rate of the pulse-period change would be $|\dot{P}| \sim 10^{-10}\text{s}/\text{s}.$

4 DISCUSSION

The results presented in the previous section show that LMC X-4 undergoes cyclical transitions between spin-up and spin-down phases, with torque reversals occurring roughly every $\sim 6.8$ years. The spin period variability could be reasonably well described by using either a sinusoidal function, which would suggest the presence of smoothly periodical variations between two values of maximum and minimum spin periods, or a slightly more complicated function, relaxing the needs of assuming a strictly periodical phenomenon. At present, given the irregular and large spacing among all data available, it is not possible to firmly distinguish among these two possibilities. Nevertheless, below we discuss briefly several possible mechanisms that could give rise to quasi-periodical torque reversals in systems like LMC X-4.

Third body. Concerning the strictly periodical case (i.e. Eq. 1), one of the most intriguing possibility is that the sinusoidal-like behaviour of the pulse period are due to the Doppler shifts produced when a binary system is orbiting around a third body. In this case, we can re-write Eq. 1 as

$$P(t) = \overline{P}_{\text{spin}} \left(1 + \frac{K_B}{c} \sin \left(2\pi \frac{t - T_0}{P_3}\right)\right),$$

where $K_B$ is the amplitude of the radial velocity of the binary system and $c$ is the speed of light. By using the results obtained in Sect. 3, we can estimate an orbital period of the inner HMXB around the third body of $P_3 \geq 5090$ days and a radial velocity of the binary of $K_B = 160 \text{ km s}^{-1}.$ The
mass of the third body, $M_3$, can be estimated from these parameters by using the "mass function":

$$M_3 = \frac{K_2^2 P_3}{2\pi G \sin (i)} (1 + q)^2 \tag{4}$$

where $q = M_B/M_3$, $M_B$ is the total mass of the binary system, $G$ is the gravitational constant, and $i$ is the inclination of the system (we assumed here the case of circular orbits for simplicity). Assuming $i = 90^\circ$ and $q \ll 1$, we can estimate from Eq. 4 a lower-limit for the mass of the third body of $M_3 \simeq 2000 M_\odot$.

Although the above finding would open the interesting possibility of LMCX-4 being part of a system hosting an intermediate mass black holes (IMBHs), we show in the following that this interpretation can be most likely ruled out.

The binary system LMCX-4 is located at a distance of $\simeq 4$ kpc from the dynamical center of the Large Magellanic Cloud. The structure of the galaxy and its kinematics are well studied and according to relatively recent works (see, e.g. van der Marel 2006; van der Marel & Kallivayalil 2014) the line-of-sight velocity of stars close to LMCX-4 with respect to the Solar System is about 300 km s$^{-1}$. We found in the literature three direct measurements of the mean line-of-sight velocity $V_{\text{LOS}}$ of LMCX-4 in different epochs: (i) $V_{\text{LOS}} = 294 \pm 5$ km s$^{-1}$ on MJD 43198 (Chevalier and Illovasky 1977), (ii) $V_{\text{LOS}} = 302 \pm 13$ km s$^{-1}$ on MJD 43475 (Hutchings et al. 1978), and (iii) $V_{\text{LOS}} = 306 \pm 10$ km s$^{-1}$ on MJD 52232 (van der Meer et al. 2007). These measurements were obtained from the analysis of the Doppler shift of absorption and emission lines registered in the optical spectrum of the donor star in this system. All these values are in a good agreement with the radial velocity distribution in the LMC galaxy and cannot easily be reconciled with the expectations of the triple system model. In the latter case, Doppler effects are expected to produce shifts of $V_{\text{LOS}}$ at different orbital phases. The measurements (i) and (ii) mentioned above would correspond to the two phases of the triple system orbit $\Psi_1^H \simeq 0.52$ and $\Psi_1^H \simeq 0.23$. At these phases, the expected Doppler shifts of $V_{\text{LOS}}$ would be $\Delta V_{\text{LOS}}^H = +20$ and $\Delta V_{\text{LOS}}^H = -159$ km s$^{-1}$, respectively. This should lead to a discrepancy between the two measurements at MJD 43198 and MJD 43475 of about $\sim 180$ km s$^{-1}$, which is not observed (see also Fig. 3).

As an additional test of the triple system hypothesis, we considered all the mid-eclipse times measured by different instruments throughout the entire history of X-ray observations of LMCX-4 (Molkov et al. 2015). If the source was orbiting a third body, sinusoidal-like residuals would be expected after the long-term evolution of the orbital period is removed from the fit to the data. The plot in Fig. 3 shows that this is not the case. In the same figure we also show that the amplitude of the sinusoidal modulation expected for a third body with the orbital period $P_3$ estimated in Sect. 3 would be much larger than the uncertainty on all available measurements. Indeed, based on our previous calculations in this section, the orbital radius of the third body should be $R_3 = K_2 P_3/(2\pi) \simeq 1.2 \times 10^{10}$ km, leading to a maximum light travel time delay of $\sim 10.3$ h.

**Variations of the accretion rate.** The hypothesis discussed above implies apparent changes in the spin frequency. At the same time in binary systems there are mechanisms and processes that could directly change the rotation rate of a neutron star. The most important of them is connected with the transfer of the angular momentum between the accreted matter and the neutron star, i.e. the "accretion torque". The balance between these concurrent processes depends on many factors, the dominant one being usually the accretion rate. It is generally assumed that the neutron star in LMCX-4 accretes from a disk, and thus a number of different models for the estimate of the accretion torque can be adopted to estimate the expected spin-up/spin-down rate (see, e.g., Ghosh & Lamb 1979; Lovelace et al. 1995; Wang 1995, etc.). In the majority of these models, a substantial change in the spin of the neutron star requires a large variation of the mass accretion rate, which in turns leads to comparable changes in the X-ray luminosity. This is at odds with respect to the findings obtained from the long-term observations of LMCX-4, which show that the source does not display a significant variation in the X-ray luminosity during the torque reversal events.

**Recycling magnetosphere model.** A different possibility to interpret the regular torque reversals observed from LMCX-4 without assuming a strong variations of the mass accretion rate is offered by the so-called "recycling magnetosphere model" presented in Perna et al. (2006). These authors showed that when the magnetic axis of the compact object is inclined with respect to its rotational axis and the direction normal to the plane of the disk, accretion onto the neutron star cannot proceed smoothly. As for an inclined dipole the magnetospheric boundary regulating the interaction between the compact object and the accretion disk is elongated, it might occur that accretion only takes place during a few spin rotational phases, while in other the inflowing
material is preferentially ejected from the system due to the onset of the propeller effect. Depending on the strength of the propeller, part of the ejected material can be unbound completely from the system or fall back onto the disk and contribute to enhance the accretion at a later stage onto the neutron star. Different model parameters (the neutron star spin period, magnetic field strength, inclination angle, and mass accretion rate) can give rise either to a system in which accretion prevails for most of the time and the neutron star shows a strong spin-up phase, or systems in which the ejection/recycling are the predominant interaction mechanisms and a torque reversal to a spin down phase is observed.

Perna et al. (2006) showed that, even with a constant mass inflow rate, the secular effects produced by a recycling magnetosphere would induce periodical switches between spin-up and spin-down episodes in a quasi-periodical fashion. The frequency of the torque reversals depend on all system parameters, but range typically from few to tens of years due to the large moment of inertia of the neutron star. In a few cases, torque reversals have been predicted to occur at constant X-ray luminosities (see, e.g., the case of 4U 1626-67), while in others a significant change in the overall X-ray intensity of the source was observed (e.g., GX 1+4). This matches the observational results reported in the literature for a number of X-ray pulsars in binary systems (see, e.g., Chakrabarty et al. 1977; Fritz et al. 2006; Camero-Arranz et al. 2010, and references therein). The addition of a long-term modulation of the mass accretion rate could also produce additional complications in the resulting sequence of torque reversals, as well as in the X-ray luminosity variability occurring at the time of the spin-up/spin-down transitions. A more quantitative comparison between the torque reversals observed from LMCX-4 and the predictions of the recycling magnetosphere model requires the analysis of the source luminosity across all historical X-ray observations and particularly during the torque reversal episodes. As these measurements are strongly dependent from the responses of the different instruments, a different re-analysis of all data sets is necessary to obtain fully comparable values. This is beyond the scope of the present work.

Different states of the neutron star magnetosphere. Another possibility to interpret the quasi-periodical variations of the pulse period observed in LMCX-4 is related with processes in the interior of the neutron star or within its magnetosphere. Slow variations of the spin-down rate on time scales ranging from months to years, i.e. the so-called “timing noise”, have been observed from isolated neutron stars practically since their discovery (mainly in the radio domain). The shape of these low-frequency variations changes with time and resemble a quasi-periodical signal (for review see, e.g., Hobbs et al. 2010, and references therein) or even a more strictly periodical modulation (Kerr et al. 2016). This is closely reminiscent of what we are observing from LMCX-4. The physical phenomenon causing the timing noise has not been well established yet. One of the most credibly possibility is that of the so-called “state switching” model, where the timing noise is driven by changes in the pulsars magnetosphere (Lyne et al. 2010). This model assumes that there are two (or more) states of the neutron star magnetosphere with different parameters regulating the spin-down rate. The neutron star can persist in any of these states even for a long time but the switch between states occurs abruptly. Assuming that such processes take place also in LMCX-4, it is reasonable to assume that changes in the coupling between the neutron star and the disk in the different states can lead to substantial changes in the pulse period. Even though this is only a speculative idea and more refined investigations are needed to eventually confirm its validity, we note that recent observations of the transient X-ray pulsar V0332+53 suggested that possible switches between different interaction states of the neutron star magnetosphere and the accretion disks can take place in X-ray pulsars (Doroshenko et al. 2016).

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