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The recent pulse period evolution of SMC X-1

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Abstract. We report observations of SMC X-1 in three new high-intensity states with *ROSAT HRI* in December 1995, May 1997, and March 1998 in which pulsations with a period of 0.70769 (± 0.00006) s, 0.70706 (± 0.00001) s, and 0.706707 (± 0.00001) s respectively were detected. Combining the pulse periods from observations with *ROSAT PSPC* in high-intensity states in October 1991 and March 1998, respectively, we obtain the spin-up rate of the pulsar in recent 6.5 years, $-\dot{P} = (1.18 \pm 0.06)\ 10^{-11}\ s\ s^{-1}$, consistent with the average spin-up rate $-\dot{P} = 1.2\ 10^{-11}\ s\ s^{-1}$ determined from previous measurements indicating that the stable spin-up has continued. Pulsations with a period of 0.709103 (± 0.000003) s were also detected ∼2 weeks after an X-ray turn-off during an X-ray low-intensity state in October 1991, and the period derivative derived within ∼ 10 days is $-\dot{P} \simeq (1.1 \pm 0.7)\ 10^{-11} ss^{-1}$. This is consistent with a constant accretion torque in sign and magnitude. The magnitude of the magnetic moment of the pulsar is discussed based on different description of the apparent spin-up behavior.

Key words: Accretion, accretion disk – stars: individual: SMC X-1 – stars: magnetic fields – stars: neutron – stars: rotation – X-rays: stars

1. Introduction

SMC X-1 was detected during a rocket flight (Price et al. 1971). The discovery of eclipses with the *Uhuru* satellite with a period of 3.89 days (Schreier et al. 1972) established the binary nature of the source. The optical counterpart Sk 160 has been identified as a B0 I supergiant (Webster et al. 1972; Liller 1973). Optical photometry indicated the presence of an accretion disk influencing the optical light curve (van Paradijs & Zuiderwijk 1977). In X-rays both low- and high-intensity states have been observed with an X-ray luminosity L_x varying from $\sim 10^{37}$erg s^{-1} to $\sim 5 \times 10^{38}$erg s^{-1} (Schreier et al. 1972; Tuohy & Rapley 1975; Seward & Mitchell 1981; Bonnet-Bidaud & van der Klis 1981). Angelini et al. (1991) discovered an X-ray burst from SMC X-1 probably from type II like in the Rapid Burster generated by an instability in the accretion flow. A ∼ 60 day quasi-periodicity was suggested by Gruber & Rothschild (1984) from *HEAO 1 (A4)* data, and was confirmed by more recent *RXTE* observations (Levine et al. 1996; Wojdowski et al. 1998). A pulse period of $P = 0.71$ sec (Lucke et al. 1976), neutron star mass $M_{\rm x} = 0.8 - 1.8 M_\odot$, companion mass $M_{\rm c} \approx 19 M_\odot$ and companion radius $R_{\rm c} \approx 18 R_\odot$ (Primini, Rappaport & Joss 1977) are well established. A decay in the orbital period $\dot{P}_{\rm orb}/P_{\rm orb} = (-3.36 \pm 0.02) \times 10^{-6} yr^{-1}$ was found (Levine et al. 1993), probably due to tidal interaction between the orbit and the rotation of the companion star, which is supposed to be in the hydrogen shell burning phase. Li & van den Heuvel (1997) argued that the magnetic moment in SMC X-1 may be low like that of the bursting pulsar GRO J1744-28, i.e. $\sim 10^{29}\ G\ cm^3$.

2. Observations

The observations reported in this paper have been performed with the *PSPC* and *HRI* detectors of the *ROSAT* satellite (Trümper 1983). In Table 1 a log of the observations analysed in this work is given. The observations were centered on SMC X-1. The October-1991 observations and the June-1993 observation have been retrieved from the public *ROSAT* archive in November 1997. The *ROSAT HRI* observations were made by the first author of this paper. The recently discovered transient RX J0117.6-7330 located ∼ 5′ southeast of SMC X-1 (Clark, Remillard & Woo 1996) has not been detected in these observations.

2.1. High- and low-intensity X-ray states

SMC X-1 has been observed during the *ROSAT* all-sky survey (Kahabka & Pietsch 1996). The source was in a low-intensity state in a first pointed observation, and was found in a high state in a *ROSAT PSPC* pointing in October 1991, preceding the low-intensity state by ∼12 days. This limits the duration of this specific X-ray turn-off phase to less than 2 weeks. In this paper the pulse periods

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of SMC X-1 during three X-ray high states observed with the *ROSAT HRI* ∼4, ∼5.5, and ∼6.5 years after the 1991 high state observation are reported. Pulse period determinations from the *ROSAT* observations are summarized in Table 1.

2.2. Pulse periods and period derivatives

We have searched for the pulse period in the data from four high state data and from the low state data following the first high state. In the present analysis the event times have been projected from the spacecraft to the solar-system barycenter with standard *EXSAS* software employed (Zimmermann et al. 1994). They have also been corrected for arrival time delays in the binary orbit by use of the ephemeris and the orbital solution given in Levine et al. (1993). This takes into account the change in the length of the orbital period and of the mid eclipse ephemeris due to orbital decay (Wojdowski et al. 1998). Period uncertainties have been determined from the relation $\delta P = P/(T_{obs} \times N_{bin})$, with the exposure time T_{obs} given in Tab 1 and the number of phase bins $N_{\rm bin} = 10$.

Periods of P=0.709113 (± 0.000003) s (χ^2=3000, 9 degrees of freedom), P=0.708600 (± 0.000002) s (χ^2=980, 9 degrees of freedom), P=0.70769 (± 0.00006) s (χ^2=56, 9 degrees of freedom), P=0.707065 (± 0.000010) s (χ^2=113, 9 degrees of freedom) and P=0.70670 (± 0.00002) s (χ^2=250, 9 degrees of freedom) have been obtained during the October-1991, June-1993, December-1995, May-1997 and the March-1998 high-intensity states, respectively (cf. Figure 1 and Table 1). From the October-1991 to the December-1995 high state a change in pulse period with a mean $-\dot{P} = (1.08 \pm 0.05)\ 10^{-11}\ s\ s^{-1}$ and from the June-1993 to the March-1998 high state a mean $-\dot{P} = (1.25 \pm 0.08)\ 10^{-11}\ s\ s^{-1}$ are derived.

The period derivative derived over the ∼6 year interval from October-1991 to Mar-1998 is $-\dot{P} = (1.18 \pm 0.06)\ 10^{-11}\ s\ s^{-1}$ consistent with the mean $-\dot{P} = 1.20\ 10^{-11}\ s\ s^{-1}$ derived from previous observations (Levine et al. 1993). The evolution of the pulse period with Julian date using data from Henry & Schreier (1977), Kunz et al. (1993), Levine et al. (1993), Wojdowski et al. (1998) and the results from this work is given in Figure 2. Also shown are the residuals compared to a linear best-fit with a $-\dot{P} = 1.153\ 10^{-11}\ ss^{-1}$. It is very evident that the pulse period of SMC X-1 undergoes a period walk with a time scale of a few 1000 days (a few years). But the amplitude of this period walk is small ($\sim 1.5\ 10^{-4}\ s$). It may be suspected that somewhere at the end of 1994 the "positive" deviation from the mean $\dot{P}$ was largest (cf Figure 2). After this time the mean $\dot{P}$ may have increased. It is not clear in which way the period walk continues. An explanation of this period walk in terms of a "free" precessing neutron star is unlikely (cf. Bisnovatyi-Kogan & Kahabka 1993).

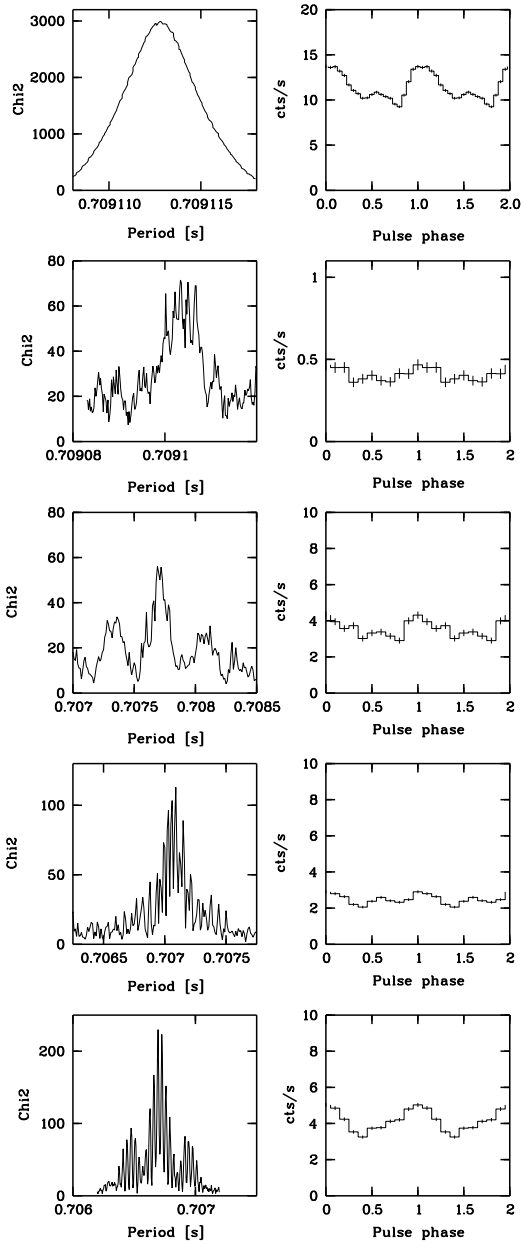

Fig. 1. χ^2 distribution and pulse profile for period search applied to period data of SMC X-1 in Oct-1991 (high, low-state), Dec-1995, May-1996 and Mar-1998 (from top to bottom). Pulse phase 1.0 referes to the pulse maximum.

A pulse period search has also been performed in an observation during a low-intensity state performed in the time interval 16 to 19 Oct-1991 (cf. Table 1 and Figure 1). A period of P=0.709103 ± 0.000003 s (χ^2=71, 9 degrees of freedom) has been determined (cf. Figure 1). This period is close to the period determined during the 7-Oct to 8-Oct-1991 high-intensity state and consistent with the long-term negative $\dot{P}$ value. The significance of this period is 8σ. The period derivative between the high and low state

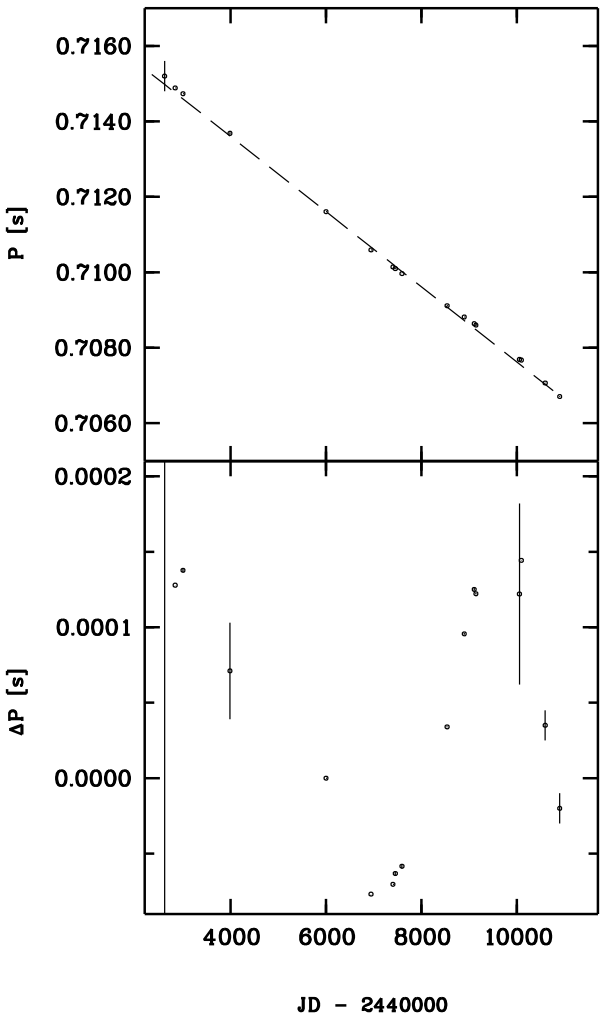

Fig. 2. Upper panel: 22.7 year pulse period history of SMC X-1 as a function of Julian date. Values are shown for observations with *Apollo-Soyuz*, *SAS-3*, *Ariel V*, *Einstein*, *EXOSAT*, *Ginga*, *HEXE*, *ROSAT*, *ASCA*, and *RXTE* (cf. Table 2 for a summary). The best-fit mean $-\dot{P} = 1.153\ 10^{-11}\ ss^{-1}$ is given as dashed line. Lower panel: Residuals of least-square linear fit to the period values.

in Oct-1991 (with a time interval $\sim$ 10 days) is $-\dot{P} \simeq (0.4 - 1.8)\ 10^{-11} s\, s^{-1}$.

3. Discussion

Disk-fed magnetic neutron stars have been predicted to experience spin-up or spin-down episodes due to the torque exerted by the accretion disk. In the magnetically-threaded accretion disk model, first suggested by Ghosh & Lamb (1979a, 1979b), the spin-up rate $-\dot{P}$ is given by

$$-2\pi I\dot{P}/P^2 = \dot{M}(GMr_0)^{1/2} n(\omega_s), \quad (1)$$

where I is the moment of inertia of the neutron star, $\dot{M}$ the accretion rate, G the gravity constant and r_0 the inner edge of the accretion disk. The dimensionless torque $n(\omega_s)$, which includes the torque contribution from both matter accretion and magnetic stress, is a function of the "fastness parameter" $\omega_s \equiv (r_0/r_c)^{3/2}$, where $r_c \equiv (GMP^2/4\pi^2)^{1/3}$ is the corotation radius.

With the *mean* spin-up rate and X-ray luminosity observed in SMC X-1, equation (1) has two sets of solutions: (1) the magnetic moment of the pulsar μ is less than a few $10^{29} G\, cm^3$ with $r_0 \ll r_c$; (2) μ is around $10^{30} G\, cm^3$ with $r_0 \sim r_c$ (Li & van den Heuvel 1997). If the X-ray intensity during the low state, which is lower than that during the high state by a factor of $35 - 50$, is due to a reduction in the mass accretion rate, the condition $r_0 \leq r_c$ implies $\mu \lesssim 2 \times 10^{29} G\, cm^3$. However, Gruber & Rothschild (1984; see also Levine et al. 1996; Wojdowski et al. 1998) have suggested the possibility of modulation of the observed X-ray intensity by a tilted, precessing, accretion disk like that in Her X-1 (Katz 1973), which would imply that the intrinsic X-ray luminosity or mass accretion rate of the pulsar could be quite steady. In this case the pulsar magnetic moment may lie between $10^{29} G\, cm^3$ and $10^{30} G\, cm^3$, though a magnetic moment as high as $\sim 10^{30} G\, cm^3$ seems less likely for SMC X-1, because of the following arguments. As seen in Fig. 2, the spin-up rate of the pulsar in 1980s and 1990s varied around its mean value by $\sim$ 20%.

Table 2. Periods and period residuals from least-square linear fit for observations of SMC X-1. The periods derived from the *Einstein* and *HEXE* observations have not been corrected for orbital decay.

Mission	JD - 2440000	Pulse period [s]	Residual [s]	Ref.
Uhuru	1114.7	0.71748(26)	+0.00100	[1]
Apollo -Soyuz	2614.3	0.7152(4)	+0.00022	[1]
SAS 3	2836.7	0.71488585(4)	+0.000128	[2]
Ariel V	3000.2	0.7147337(12)	+0.000138	[2]
Einstein	3986.4	0.713684(32)	+0.0000710	[2]
EXOSAT	5999.0	0.7116079958(4)	+0.000000	[3]
Ginga	6942.0	0.710592116(36)	–0.0000769	[2,4]
Ginga	7401.2	0.710140670(15)	–0.0000703	[2,4]
HEXE	7452.0	0.7100978(15)	–0.0000632	[3]
HEXE	7591.5	0.7099636(15)	–0.0000584	[3]
ROSAT	8537.1	0.70911393(34)	+0.0000340	[2]
ROSAT	8897.2	0.7088166(6)	+0.0000956	[2]
ASCA	9105.0	0.7086390(9)	+0.000125	[2]
ROSAT	9142.0	0.7085992(5)	+0.000122	[2]
ROSAT	10054.5	0.70769(6)	+0.000122	[5]
RXTE	10093.5	0.70767330(8)	+0.000144	[2]
ROSAT	10594.3	0.707065(10)	+0.0000350	[5]
ROSAT	10898.7	0.706707(10)	–0.0000200	[5]

Ref.: [1] Henry & Schreier 1977; [2] Wojdowski et al. 1998; [3] Kunz et al. 1993; [4] Levine et al. 1993; [5] this work.

Table 1. *ROSAT* observations of SMC X-1

Instr.	ID	Time start - end (UT)	(JD - 2440000)	Expos. (ksec)	Pulse period (s)	State
PSPC	400022p	7-Oct-1991 04:09 - 8-Oct-1991 02:41	8536.673 - 8537.612	16.6	0.709113±0.000003	High
PSPC	600197p	16-Oct-1991 07:34 - 19-Oct-1991 23:32	8545.815 - 8549.481	22.1	0.709103±0.000003	Low
PSPC	400022p-2	3-Jun-1993 00:03 - 4-Jun-1993 04:40	9141.502 - 9142.694	11.8	0.708600±0.000002	High
HRI	500420h-2	2-Dec-1995 23:09 - 2-Dec-1995 23:39	10054.465 -10054.486	1.08	0.70769±0.00006	High
HRI	500420h-4	15-May-1997 13:36 - 4-Jun-1997 22:29	10584.067 -10604.437	4.89	0.707065±0.000010	High
HRI	500420h-5	25-Mar-1998 17:03 - 26-Mar-1998 17:09	10898.210 -10899.214	4.24	0.706707±0.000010	High

The most straightforward explanation for this change is that the accretion rate has fluctuated by a similar (or a bit larger) factor[1]. If $\mu \sim 10^{30} G\,cm^3$, r_0 would be so close to r_c that the pulsar would spin down when the accretion rate decreased by a small factor (less than 20%), contradicted with the steady spin-up observed.

The above arguments are based on the classical accretion torque models, which, however, has encountered difficulties in explaining the period evolution in the X-ray pulsar Cen X-3, which possesses many similarities with SMC X-1. Both pulsars are in a close binary system with a supergiant companion star overflowing its Roche-lobe, accreting from a disk (Tjemkes et al. 1986) at a high rate, with the X-ray luminosities close to or higher than the Eddington luminosity (Nagase 1989). Tidal torque between the distorted supergiant and the neutron star leads to an orbital decay at a similar rate in the two systems (cf. White et al. 1995). However, Cen X-3 exhibits a pulse period evolution quite different from SMC X-1. Prior to 1991, Cen X-3 had already been found to show a secular slow spin-up superposed with fluctuations and short episodes of spin-down. The more frequently sampled *BATSE* data show that Cen X-3 exhibits 10-100 d intervals of steady spin-up and spin-down at a much larger rate, and the long-term ($\sim$ years) spin-up trend is actually the average consequence of the frequent transitions between spin-up and spin-down (Finger et al. 1994). Such spin behavior has been found in at least 4 out of 8 persistent X-ray pulsars observed with *BATSE* (Bildsten et al. 1997), and is difficult to explain in terms of classical accretion torque models, which would require finely tuned step-function-like changes in the mass accretion rate.

It is interesting to see whether the secular spin-up in SMC X-1 actually consists of transitions of short-term spin-up and spin-down, as in Cen X-3. If it is the case, this would indicate a larger instantaneous accretion torque, and hence a higher magnetic moment.

[1] Due to disk precessing, the accretion torque also changes, but on a timescale much shorter than that of the pulse period variation.

4. Summary

New values for the spin period of SMC X-1 have been determined during recent *ROSAT* observations. These observations clearly show that the steady spin-up of the neutron star has continued. This makes SMC X-1 the exceptional X-ray pulsar in which no spin-down episode has been observed, though it is still unknown whether this spin-up occurs in reality or it is just an apparent superposition of more frequent spin-up and spin-down episodes. The magnetic moment of the pulsar could be as small as $\sim 10^{29} G\,cm^3$ if its spin trend can be described by classical accretion torque models. Detailed timing observations are strongly recommanded to resolve this subject, and will have important implications on the theoretical models for angular momentum transfer between a magnetic neutron star and the surrounding accretion disk.

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