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Letter to the Editor

On the nature of SMC X-1

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Abstract. The 0.71 s X-ray pulsar SMC X-1 has some distinct features from other X-ray pulsars. It maintained a stable spin-up though in X-rays both low- and high-intensity states have been observed. An X-ray burst was discovered from SMC X-1, and was probably generated by an instability in the accretion flow. Using the modified magnetically threaded accretion disk theory, we have estimated the magnetic moment of SMC X-1 to be $\sim 10^{29}$ G cm^3, which is lower than those of other typical X-ray pulsars (e.g., Her X-1, Vela X-1) by an order of magnitude. Comparing SMC X-1 with the new transient X-ray pulsar GRO J1744-28, from which type II bursts were recently discovered, we suggest that the nature of this type of "bursting pulsars" may be accounted for by their relatively low magnetic moments and high accretion rates, if the burst from SMC X-1 is really due to spasmodic accretion as those from GRO J1744-28. The inner edge of the accretion disk in both X-ray sources is found to lie in the transition region at which the radiation pressure becomes comparable to the gas pressure, suggesting that the bursts from both sources may be related to the Lightman-Eardley instability in the inner region of the disk. The difference between the one burst from SMC X-1 and the many bursts from GRO J1744-28 is discussed, and may originate from the different magnetic field structure in these two X-ray pulsars.

Key words: accretion, accretion disks – binaries: close – stars: neutron – pulsars: SMC X-1

1. Introduction

The 0.71s X-ray pulsar SMC X-1 was originally detected during a rocket flight by Price et al. (1971). It is in a 3.9 day binary containing a B0 supergiant companion (Sk 160: Schreier et al. 1972). The X-ray pulsar is eclipsed by the supergiant for $\sim$ 0.6 day. Pulse-timing studies yield a projected orbital radius $a_{\rm x} \sin i$ = 53.46 ± 0.05 lt-sec, neutron star mass M = $0.8 - 1.8 M_{\odot}$, companion mass $M_{\rm c} \simeq 19 M_{\odot}$, and companion radius $R_{\rm c} \simeq 18 R_{\odot}$ (Primini et al. 1977). A recent precise X-ray timing observation of SMC X-1 with Ginga discovered a decay in the orbital period at a rate of $\dot{P}_{\rm orb}/P_{\rm orb}$ = $(-3.36 \pm 0.02) \times 10^{-6}$ yr^{-1}, which might be driven by tidal interactions between the orbit and the rotation of the companion (Levine et al. 1993).

Some interesting features have been observed from SMC X-1. First, SMC X-1 is at times one of the most powerful X-ray pulsars, exhibiting both low- and high-intensity states, with a range of X-ray luminosity $L_{\rm x}$ from 10^{37} erg s^{-1} or less (Seward & Mitchell 1981; Bonnet-Bidaud & van der Klis 1981) up to $\sim 10^{39}$ erg s^{-1} (Price et al. 1971; Ulmer et al. 1973; Coe et al. 1981). The latter is $\sim$ 5 times higher than the Eddington critical luminosity for a spherically accreting neutron star with mass of 1.4 $M_{\odot}$. Meanwhile, SMC X-1 is the only X-ray pulsar showing steady spin-up (at an average rate of $\dot{P}_{\rm s} \simeq -1.2 \times 10^{-11}$ s s^{-1}, Kunz et al. 1993) without spin-down episodes observed. Second, an X-ray burst was disovered in SMC X-1 by Angelini et al. (1991), and was believed to be possibly related to the type II bursts observed from the Rapid Burster, originating from an instability in the accretion flow (Lewin, van Paradijs & Taam 1993, 1995). Type II bursts were recently discovered from a new transient X-ray source GRO J1744-28 near the Galactic Center (Fishman et al. 1996; Kouveliotou et al. 1996; Lewin et al. 1996), which was later identified as a 0.467 s X-ray pulsar in a binary system with an orbital period of 11.8 days (Finger et al. 1996). In this sense, SMC X-1 and GRO J1744-28 belong to the peculiar group of "bursting pulsars", showing both pulsed X-ray emission and (possible) type II bursts. In this paper we derive the magnetic moment of SMC X-1 in section 2, from its spin history by use of the modified accretion torque theory. In section 3 through comparing the properties of SMC X-1 with those of GRO J1744-28, we show that there are some special features in these two sources which make them different from other accreting neutron stars.

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2. The magnetic moment of SMC X-1

We assume that there is a disk formed around SMC X-1. The observational evidence for the existence of an accretion disk due to the atmospheric Roche lobe overflow from the massive primary (Savonije 1979) includes the elliptical light curve (van Paradijs & Zuiderwijk 1979; van der Klis et al. 1982; Howarth et al. 1982; Tjemkes et al. 1986) and the considerable excess of the X-ray luminosity over the maximum calculated for wind-driven accretion (Lamers et al. 1976; Petterson 1978). The secular stable spin-up also indicates that angular momentum has been transferred to the neutron star from a surrounding disk rather than from a wind. The 60 day quasi-periodicity in the X-ray emission of SMC X-1, originally found by Gruber & Rothschild (1984) and recently confirmed by Levine et al. (1996) and Zhang et al. (1996), supports the presence of an accretion disk, by analogy with the long-term cycles of Her X-1 and LMC X-4, whose variability may be caused by shadowing of the line of sight by a tilted (or twisted) processing disk (Katz 1973; Petterson 1975; Gerend & Boynton 1976).

In the magnetically threaded disk model originally proposed by Ghosh & Lamb (1979a, b), the change in the neutron star's spin period P_s is governed by the following equation

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

where I and $\dot{M}$ are the moment of inertia and the accretion rate of the neutron star, respectively, G the gravity constant and r_0 the inner edge of the accretion disk. The dimensionless torque $n(\omega_s)$ is a function of the fastness parameter $\omega_s \equiv (r_0/r_{co})^{3/2}$, where $r_{co} \equiv (GM{P_s}^2/4\pi^2)^{1/3}$ is the corotation radius. When ω_s increases from 0 to 1, the torque varies from being positive to negative; and there exists a critical value ω_c of ω_s at which the torque vanishes. Recent studies (Wang 1995; Li & Wang 1996) on the disk-field interaction based on the Ghosh & Lamb model have shown that the possible form of $n(\omega_s)$ may lie between

$$n(\omega_s) = \frac{(5/3) - (7/3)\omega_s}{(1-\omega_s)}, \quad (2)$$

and

$$n(\omega_s) = \frac{(7/6) - (4/3)\omega_s + (1/9){\omega_s}^2}{(1-\omega_s)}, \quad (3)$$

with the corresponding value of ω_c being 0.71 and 0.95, respectively.

The inner edge r_0 of the accretion disk can be roughly described in terms of the Alfvén radius for spherical accretion (Wang 1996; Li 1997)

$$r_0 \simeq r_A \equiv \mu^{4/7}\dot{M}^{-2/7}(2GM)^{-1/7}, \quad (4)$$

where μ is the magnetic moment of the neutron star.

Knowing P_s, $\dot{P}_s$ and L_x, we may use Eqs. (1)-(4) to derive the magnetic moment for an X-ray pulsar. The calculated values of the magnetic moment (μ_{30}) in units of 10^{30} G cm^3 of SMC X-1 are shown in solid curves in Fig. 1, as a function of the X-ray luminosity (L_{37}) in units of 10^{37} erg s^{-1}. The curves labeled

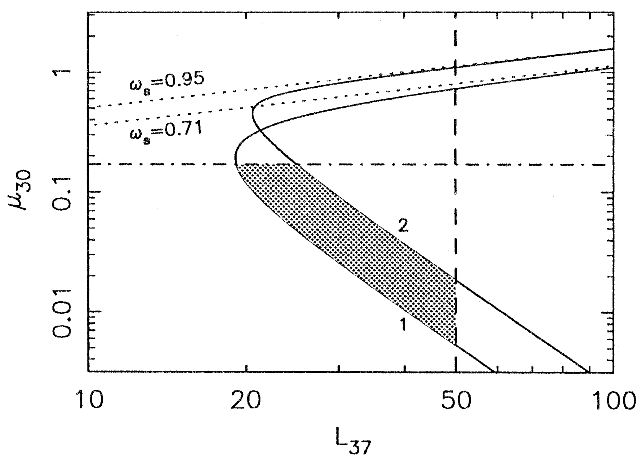

Fig. 1. Relations between the mean X-ray luminosity L_{37} and the magnetic moment μ_{30} of SMC X-1. The shaded curved band shows the magnetic moment that would produce the spin-up rate observed, as a function of L_{37}. The solid curves labeled 1 and 2 are respectively calculated from Eqs. (2) and (3), which provide a confinement of the possible accretion torque. The upper limit of the mean X-ray luminosity is assumed to be L_{37} = 50, plotted as the dashed line. The two dotted lines represent the $\mu_{30} - L_{37}$ relation as the fastness parameter ω_s reaches its critical value ω_c related to Eqs. (2) and (3). The dot-dashed line gives an upper limit of μ_{30}, if the turn-off luminosity is assumed to be L_{37} = 1.

1 and 2 are results from Eqs. (2) and (3), respectively. Typical parameters of a neutron star (M = 1.4$M_\odot$, R = 10^6 cm and I = 10^{45} g cm^2) have been adopted in the calculation.

As shown in Fig. 1, there exist a range of values of μ and L_x, lying between the two solid curves, to account for the secular spin-up in SMC X-1. Since we have used the mean spin-up rate in the calculation, the magnetic moment should be determined by the X-ray luminosity averaged over both high- and low-intensity states, whose typical duration and frequency are somewhat uncertain because of the scant coverage of SMC X-1. Here we have assumed that the X-ray luminosities during high- and low-intensity states are 5 × 10^{38} and 10^{37} erg s^{-1}, respectively. The upper limit of the mean X-ray luminosity is then constrained by $L_{37} \leq 50$. The accretion torque model presents a lower limit $L_{37} \simeq 20$ in Fig. 1. Thus the mean X-ray luminosity is close to or larger than the Eddington limit. Each solid curve yields two solutions of μ_{30} and ω_s for a given value of L_{37} ranging from 20 to 50. For example, when L_{37} = 50, curve 1 gives $\mu_{30} \simeq 5\times10^{-3}$, $\omega_s \simeq 1\times10^{-2}$, or $\mu_{30} \simeq 0.7$, $\omega_s \simeq 0.65$; while curve 2 gives $\mu_{30} \simeq 2\times10^{-2}$, $\omega_s \simeq 3\times10^{-2}$, or $\mu_{30} \simeq 1$, $\omega_s \simeq 0.92$. The latter solution in each case, which provides a seemingly normal magnetic moment (e.g.,Wang 1996), is in fact unreasonable, since the value of ω_s is so close to ω_c (0.71 or 0.95, see dotted lines in Fig. 1) that a small change (less than 20%) in the X-ray luminosity can easily move the pulsar from spin-up to spin-down, contradicted with the steady decrease of the pulse period, which implies that SMC X-1 should at least be a slow rotator during the high state (Darbro et al. 1981).

Further constraint on the magnetic moment results from the X-ray luminosity in the low-intensity state. It is known that in order for accretion to occur, the inner edge of the accretion disk should be smaller than the corotation radius, i.e., $r_0 \leq r_{\rm co}$, otherwise the centrifugal force will inhibit the accretion matter to enter the neutron star magnetosphere. So there exists a critical luminosity below which the X-rays will turn off (Stella et al. 1986). For SMC X-1 we take the luminosity ($L_{37} \simeq 1$) in low-intensity state as the turn-off luminosity, and obtain that the upper limit of the magnetic moment is $\mu_{30} \simeq 0.17$, which is plotted as the dot-dashed line in Fig. 1. Combined with the constraints on L_{37}, this yields a possible range of the magnetic moment $\mu_{30} \sim (5 \times 10^{-3} - 0.17)$, shown as the shaded band in Fig. 1. However, the value of μ_{30} can not be much smaller than 0.1, because the nature of an X-ray pulsar requires SMC X-1 to possess a magnetic field at least stronger than 10^{10} G. A 7-year monitoring of SMC X-1 with the Vela 5B satellite (Whitlock & Lockner 1994) gives an average 3-12 keV luminosity of 2×10^{38} erg s^{-1}, suggesting $\mu_{30} \simeq 0.1$ from Fig. 1.

3. Comparison between SMC X-1 and GRO J1744-28

The above-derived value of μ of SMC X-1, though clearly model dependent, is an order of magnitude lower than the X-ray pulsars such as Her X-1 and Vela X-1, with a high (a few 10^{30} G cm^3) magnetic moment from the cyclotron spectral lines detected (White, Nagase & Parmar 1995 and references therein). From the spin history of GRO J1744-28, Daumerie et al. (1996) derived its magnetic moment similar to that of SMC X-1. Other similarities between SMC X-1 and GRO J1744-28 lie in the pulse periods (0.71 s and 0.467 s respectively), and the mean X-ray luminosities that were at or above the Eddington limit. Perhaps the most striking feature is that both sources showed X-ray bursts which are probably of the same origin, that is, related to type II bursts from the Rapid burster.

Energetics arguments, the shape and evolution of the burst spectra suggest that the bursts in GRO J1744-28 are almost certainly not type I bursts (thermonuclear flashes), and are most probably due to gravitational potential energy (type II bursts), caused by accretion disk instabilities (Kouveliotou et al. 1996; Lewin et al. 1996). The burst in SMC X-1, as argued by Angelini et al. (1991), is unlikely to be a type I burst because of the inconsistency between the burst spectrum and a blackbody, and no spectral softening during the decay of the burst. The lack of spectral evolution and the decrease in the persistent emission following the burst are reminiscent of type II bursts.

A possible mechanism that invokes for type II bursts is the Lightman & Eardley (LE) instability (Lightman & Eardley 1974), which develops in viscous accretion disks when the radiation pressure becomes comparable to the gas pressure. Global, nonlinear evolution of accretion disks that are LE unstable has been investigated by Taam & Lin (1984) and Lasota & Pelat (1991). The light curve predicted by these authors is qualitatively similar to the burst profile and the decline of the persistent emission level for type II bursts. Recent calculations by Cannizzo (1996) demonstrate that, in order for the outbursts in GRO J1744-28 to occur, the rate of accretion at the inner edge of the disk must be within a narrow range just above the critical accretion rate at which the radiation pressure begins to become significant. In other words, r_0 should only be smaller than the transition radius $r_{\rm tr}$ at which the radiation pressure equals the gas pressure by some marginal amount.

To examine the above idea, one can easily derive the ratio of r_0 to $r_{\rm tr}$ as follows, using the standard α-disk model (Shakura & Sunyaev 1973),

$$r_0/r_{\rm tr} \simeq 1.3(\alpha/0.1)^{-2/21}\mu_{29}^{4/7}L_{38}^{-22/21} \quad (5)$$

for a neutron star accretor with typical parameters. The magnetic moment and luminosity of SMC X-1 and GRO J1744-28 imply $r_0 \simeq r_{\rm tr}$, satisfying the condition for LE instability. This makes them distinct from other X-ray pulsars and the neutron stars in low-mass X-ray binaries. For persistent low-mass X-ray binaries, whose X-ray luminosities are comparable to SMC X-1 and GRO J1744-28, but whose magnetic moments are much lower, one would expect $r_0 \ll r_{\rm mi}$, and the outbursts due to the LE instability could not occur. Such bursts would not occur in normal binary X-ray pulsars either, since the inner edge of the accretion disk in such systems, due to the higher pulsar's magnetic moment ($\sim 10^{30}$ G cm^3), is located in the gas pressure dominated region. Additionally, there exist a group of X-ray pulsars with $\sim 6-9$ s pulse-period and intermediate ($\sim 10^{29}$ G cm^3) magnetic moment (Mereghetti & Stella 1995; van Paradijs, Taam & van den Heuvel 1995). But their low X-ray luminosities ($\sim 10^{35} - 10^{36}$ erg s^{-1}) also lead to $r_0 > r_{\rm tr}$. If the bursts in the Rapid Burster can also be accounted for by the LE instability, and the persistent X-ray luminosity is $\sim 6 \times 10^{36}$ to $\sim 3 \times 10^{37}$ erg s^{-1} (Lewin et al. 1996), its magnetic moment can be estimated to be $\sim (10^{26} - 10^{28})$ G cm^3.

Our suggestion of a possible connection between SMC X-1 and GRO J1744-28 strongly depends on the assumption that the burst in SMC X-1 is of similar nature to those from GRO J1744-28. However, one should admit that even if it is true, there is a huge difference in the detailed characteristics of the bursts from them. The most striking one is that GRO J1744-28, like the Rapid Burster, produced bursts at a very high rate (one every three minutes in December 1995 and in June 1996); while there is only one burst[1] reported in SMC X-1. There is also a large difference in the burst luminosities. It approached $\sim 50 - 100$ times Eddington limit for the most luminous bursts from GRO J1744-28 if the distance is assumed to be 8 kpc (Briggs et al. 1996; Giles et al. 1996); and the peak luminosity in SMC X-1 during the burst was 8.5×10^{38} erg s^{-1} (for a distance of 50 kpc). Furthermore, there is a distinct dip after the burst from GRO J1744-28 (as is the case in the type II bursts from the Rapid Burster). Such a dip (lasting hundred of seconds) is rather different from the decline observed after the one burst from SMC X-1, which last more than five hours.

[1] There was a sequence of five outbursts observed with *CGRO* and *RXTE* between early October 1995 and mid-August 1996 (Zhang et al. 1996), but the nature of the bursts is unclear.

A comparison between GRO J1744-28 and the Rapid Burster by Lewin et al. (1996) showed that despite the occurrence of type II bursts in both sources, there is a significant difference in the burst pattern, which may be due to the different magnetic fields. Bearing in mind that SMC X-1 and GRO J1744-28 have a similar magnetic moment and mass accretion rate, their difference is probably associated with the different magnetic field structure. For example, in SMC X-1 the magnetic axis is nearly perpendicular to the spin axis (Leahy 1991); while in GRO J1744-28 the fact that it is most likely that we view it nearly pole-on (Daumerie et al. 1996), and that the observed pulse profile is single-peaked implies a small angle between the spin and magnetic axes.

Our model will be falsified if SMC X-1 produced a type I burst, the possibility of which can not be completely excluded. If that is the case, it then remains more mysterious why the two sources, with similar properties, produced different types of burst(s).

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