DO QUIESCENT SOFT X-RAY TRANSIENTS CONTAIN MILLISECOND RADIO PULSARS ?

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ABSTRACT

Soft X-Ray Transients (SXRTs) in outburst show properties similar to those of persistent Low Mass X-Ray Binaries (LMXRBs), and therefore likely contain an old weakly magnetic neutron star spun-up by accretion torques. We investigate the conditions under which a detectable radio pulsar signal can be produced by the rapidly rotating neutron star in the quiescent phase of a SXRT. As the mass inflow rate towards the neutron star decreases during the decay of an outburst, the radius of the neutron star magnetosphere might expand beyond the corotation radius, inhibiting accretion onto the neutron star due to the "centrifugal barrier". Hence, the minimum observed accretion-induced X-ray luminosity at the end of an outburst provides constraints on the neutron star magnetic field, B, and spin period, P. Based on current measurements, SXRTs can lie in the region of the $B-P$ diagram which is characteristic of recycled millisecond radio pulsars. If this were the case, the radio pulsar emission from a SXRT can resume only when the mass inflow rate from the companion star decreases by a few orders of magnitude below the "centrifugal barrier" threshold. The persistent emission ($\sim 10^{33}-10^{34}$ erg s^{-1}) detected in the quiescent state of a few SXRTs might result from accretion onto the neutron star surface, from accretion down to the magnetospheric radius (if the "centrifugal barrier" is closed), or from the neutron star cooling. In the latter two cases the possibility of one of these SXRTs turning on as a radio pulsar is far more likely.

Subject Headings: accretion – stars: neutron – stars: pulsars – X-rays: stars

1. INTRODUCTION

Neutron stars in LMXRBs are likely spun-up by accretion torques to limiting periods of $\sim 1-10$ ms, depending on the value of their magnetic field (e.g. Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). Once accretion stops for evolutionary reasons, the neutron star in these systems is expected to shine as a recycled radio pulsar orbiting a low mass companion. LMXRBs of this kind might therefore represent the progenitors of the weak magnetic field ($\sim 10^8-10^9$ G), millisecond radio pulsars (Backer et al. 1982; Manchester et al. 1991).

Besides persistent sources, the X-ray sky is populated by a number of transients which are quiescent and undetected for most of the time and undergo sporadic surges of accretion, typically lasting for $10-100$ d, during which they emit an intense X-ray flux and show properties similar to those of persistent X-ray sources (White, Kaluzienski & Swank 1984). The outbursts of SXRTs, in particular, are often accompanied by a pronounced increase in the luminosity of their faint optical counterparts and by the presence of type I X-ray bursts. These properties clearly associate SXRTs with LMXRBs containing an old neutron star. Their activity is likely regulated by an instability arising either in the accretion disk around the collapsed object (Lin & Taam 1984; Cannizzo et al. 1985), or in the mass transfer from the companion star (Osaki 1985; Hameury, King & Lasota 1986). In both approaches, the mass donor star fills, or almost fills, its Roche lobe and transfers mass at a relatively low time-averaged rate of $\sim 10^{14}-10^{15}$ g s^{-1}. If during the quiescent phase of SXRTs accretion stops completely, a millisecond radio pulsar might appear. Therefore, SXRTs could provide a "missing link" between accreting neutron stars and recycled millisecond pulsars (Callanan 1989; Shaham & Tavani 1991; Kulkarni et al. 1992).

In this *Letter* we investigate the conditions under which a radio pulsar signal might be produced in the quiescent state of SXRTs independent of the specific accretion instability responsible for the transient behaviour. For the accretion toward the neutron star magnetosphere, we adopt the spherical free fall approximation which provides also a description for the case of disk accretion (Ghosh & Lamb 1992). Results from a more detailed treatment will be reported elsewhere (Campana et al. 1993).

2. THE $B-P$ DIAGRAM AND THE MINIMUM ACCRETION-INDUCED LUMINOSITY

Accretion onto a rotating magnetic neutron star occurs only if the centrifugal drag exerted by the magnetosphere on the accreting material is weaker than gravity (i.e. the "propeller effect" - Illarionov & Sunyaev 1975; Lipunov 1992). This requires that the rotation velocity at the magnetospheric boundary is slower than the local Keplerian velocity. Owing to the dependence of the magnetospheric radius on the mass accretion rate, accretion can occur down to a minimum luminosity of

$$L_{\rm min}(R) = GM\dot{M}/R \simeq 4\times 10^{36}\, B_9^2\, P_{-2}^{-7/3}\, M_{1.4}^{-2/3}\, R_6^5 \quad {\rm erg\,s^{-1}}\,, \qquad (1)$$

where B_9 is the neutron star magnetic field in units of 10^9 G, P_{-2} the spin period in units of 10^{-2} s, $M_{1.4}$ the neutron star mass in units of 1.4 solar masses and R_6 its radius in units of 10^6 cm. Below this minimum accretion rate the neutron star is in the "propeller regime", the accretion flow cannot proceed beyond the magnetospheric boundary, due to the fact that the "centrifugal barrier" is closed. In this case the gravitational energy liberated per unit mass is lower and a sharp reduction of the accretion induced luminosity is produced. In this regime, matter can either accumulate or be ejected. Therefore, for a given source, the minimum observed X-ray luminosity above the "centrifugal barrier" (i.e. resulting from accretion onto the neutron star surface), $L_{\rm min}^{\rm obs}$, allows to constrain the spin period and/or the magnetic field of the neutron star. This can be illustrated in the usual $B-P$ diagram for radio pulsars (Fig. 1), where Eq. (1) is plotted for different values of $L_{\rm min}$: in order to accrete at the observed rates, a neutron star must possess a spin period and a magnetic field such as to lie to the right of the line corresponding to its minimum accretion-induced luminosity.

A further limitation is that no radio pulsars exist in the "graveyard" (see Fig. 1), i.e. the region below the "death line", $B_9 \simeq 2 \times 10^{-2}\, P_{-2}^2\, R_6^{-3}$ G (Ruderman & Sutherland 1975, Bhattacharya & van den Heuvel 1991).

The properties of neutron stars in SXRTs can thus be constrained by the value of the lowest detected X-ray luminosity during the decay of the outburst, $L_{\rm min}^{\rm obs}$. No evidence for the sharp luminosity decrease at the end of an outburst that should result from the onset of the "centrifugal barrier" has been observed so far $^+$. Therefore one can be confident that $L_{\rm min}^{\rm obs}$ is produced by accretion onto the neutron star surface. Currently available measurements range from $L_{\rm min}^{\rm obs} \sim 3 \times 10^{35}$ to $\sim 10^{37}$ erg s^{-1} (see the second column of Table 1) and are, in all cases, determined by the limiting sensitivity of the non-imaging instruments which observed the SXRT outbursts. These luminosities are quite high and the corresponding lines from Eq. (1) define relatively large regions in the $B - P$ diagram in which the neutron stars of SXRTs are potentially radio pulsars.

Four SXRTs have also been detected during quiescence, with luminosities considerably smaller than those observed at the end of their outbursts (cf. third column of Table 1). In principle, this emission could result from: (a) coronal activity of the companion star; (b) non-thermal processes powered by the rotational energy loss of a rapidly spinning neutron star; (c) thermal emission from the cooling neutron star; (d) accretion onto the neutron star surface or down to the magnetospheric radius (depending on whether the "centrifugal barrier" is open or closed).

In the case of Cen X-4 a luminosity of about 10^{33} erg s^{-1} (0.5–4.5 keV range) has been measured more than one year after the previous outburst (van Paradijs et al. 1987). For this source, possibility a seems unlikely considering that the late type low-mass companion could provide a luminosity of $< 10^{32}$ erg s^{-1} (Vaiana et al. 1981). The constraints on B and P derived from the lowest luminosity measured during the 1979 outburst ($L_{\rm min}^{\rm obs} \sim 3 \times 10^{35}$ erg s^{-1}) and Eq. (1) are strong enough to exclude also possibility b. Indeed these constraints limit the maximum pulsar spin-down luminosity to $\dot{E}_{\rm rot} \leq 10^{34}$ erg s^{-1}, which is insufficient to power the observed X-ray luminosity, $L_{\rm X}$, for $L_{\rm X}/\dot{E}_{\rm rot} \leq 10^{-3}$ as measured for PSR 1957+20 (Fruchter et al. 1992) and PSR J0437–4715 (Becker et al. 1993). The quiescent X-ray flux might originate from the release of thermal energy in the neutron star interior, which has been reheated through accretion (case c). However van Paradijs et al. (1987) discarded this possibility in the case of Cen X-4.

The quiescent X-ray luminosity of Cen X-4 is likely powered by accretion (case d). Due to the sparse X-ray coverage it is not possible to ascertain whether the persistent emission level is reached above or below the sharp luminosity decrease characterizing the onset of the "centrifugal barrier". In the former case, accretion proceeds to the neutron star surface and the constraints derived from Eq. (1) and the "death line" (see Fig. 1), virtually exclude the possibility that a radio pulsar

$^+$ Such behaviour has been observed in at least one hard X-ray transient containing an X-ray pulsar with a Be star companion (V0332+53; Stella, White & Rosner 1986).

might turn on, should the mass inflow rate decrease further. Less tight constraints are obtained if in quiescence the "centrifugal barrier" is closed. In this case the flow of matter cannot proceed beyond the magnetospheric radius, $r_{\rm m}$, and an accretion luminosity of $L(r_{\rm m}) = GM\dot{M}/r_{\rm m} \simeq 10^{34}\,\dot{M}_{15}^{9/7}\,B_9^{-4/7}\,M_{1.4}^{8/7}\,R_6^{-12/7}$ erg s^{-1} ($\dot{M}_{15}$ is the mass inflow rate in units of 10^{15} g s^{-1}) is liberated, which for an optically thick accretion disk is radiated in the UV/soft X-ray band with a typical temperature of $T \simeq 5\times10^5\,\dot{M}_{15}^{13/28}\,B_9^{-3/7}\,M_{1.4}^{5/14}\,R_6^{-9/7}$ K. In this regime, the minimum accretion induced luminosity can be estimated by requiring that the inflow is not disrupted by the radio pulsar pressure (see Sect. 3 and Eq. (3)); the threshold corresponds to $r_{\rm m} = r_{\rm lc}$ ($r_{\rm lc}$ is the light cylinder radius) and is given by

$$L_{\rm min}(r_{\rm lc}) = G\,M\,\dot{M}_{\rm lc}/r_{\rm lc} \simeq 10^{32}\,B_9^2\,P_{-2}^{-9/2}\,M_{1.4}^{1/2}\,R_6^6 \quad {\rm erg\,s^{-1}}\,. \tag{2}$$

The limit corresponding to Eq. (2) is indicated with dotted lines in Fig. 1 for selected values of $L_{\rm min}(r_{\rm lc})$. In this interpretation the neutron star of a SXRT must lie to the right of the line corresponding to the lowest detected luminosity in quiescence. This, together with the other constraints, defines a region of the $B-P$ diagram for which a radio pulsar might turn on in Cen X-4 for sufficiently low mass inflow rates.

The case of Aql X-1 and MX 0836–42 is similar to that of Cen X-4 (cf. Table 1); note the allowed regions of the $B-P$ diagram are somewhat larger. However for these two sources it cannot be ruled out that the thermal energy of the neutron star gives rise to the quiescent luminosity, in which case the latter does not provide any additional constraint on B and P.

Regarding MX 1746–20, it is generally assumed that the dim source detected in the globular cluster NGC 6440 (Hertz & Grindlay 1983) is the quiescent counterpart of the strong SXRT observed in 1971 (Cominsky et al. 1978). The minimum detected luminosity of $\sim 2\times10^{37}$ erg s^{-1} at the end of the outburst is quite high and a large region of the parameter space is therefore available for a hypothetical radio pulsar. It cannot be ruled out that MX 1746–20 contains a millisecond pulsar with $\dot{E}_{\rm rot} \sim 10^{35}$ erg s^{-1}, which for an efficiency of $\sim 10^{-2}$ could power the quiescent X-ray luminosity (cf. Tavani 1991).

It is evident that for the sources in Table 1 and despite the uncertainties in their distances, current measurements of their lowest accretion induced luminosity both at the end of an outburst and in quiescence leave open the possibility that they contain a radio pulsar. In the following we show that if a radio pulsar signal is to be produced and observed, further conditions on the inflow rates toward the neutron star must be satisfied.

3. THE ONSET OF THE RADIO PULSAR EMISSION

If at the end of an outburst the mass inflow rate decreases well below the value corresponding to $L_{\rm min}$ (and no significant accumulation of the inflowing material takes place), the magnetosphere expands until the light cylinder radius is reached. This occurs when

$$\dot{M}_{\rm lc} \simeq 3\times10^{13}\,B_9^2\,P_{-2}^{-7/2}\,M_{1.4}^{-1/2}\,R_6^6 \quad {\rm g\,s^{-1}}\,. \tag{3}$$

For lower rates the radio pulsar mechanism resumes and starts affecting the inflow of matter. Due to the flatter radial dependence of the pulsar radiation pressure ($\propto r^{-2}$) compared to the pressure of the inflow ($\propto r^{-5/2}$), matter is swept away and cannot penetrate any longer the accretion radius and/or the Roche lobe of the neutron star. We note that, for periods between 1 and 100 ms, Eq. (3) requires a mass inflow rate ~ 1.5 to ~ 4 orders of magnitude lower than the value at which the "centrifugal barrier" closes (cf. the different period dependence of Eq. (1) and Eq. (3)).

The observability of the radio pulsar signal produced when the mass transfer rate drops below the value given in Eq. (3), depends on the dispersion measure and free-free absorption of the material outside the accretion radius and/or the Roche lobe of the neutron star. Results of hydrodynamical calculations show that the visibility of a radio pulsar is strongly dependent on the inclination angle and geometry of the "pulsar cavity" and it might be time variable (Tavani & Brookshaw 1991). We adopt here a simple model for the radio signal propagation, which uses an adiabatic spherical wind approximation and the mass inflow rate given by Eq. (3). A free-free absorption optical depth of < 1 is obtained for

$$B_9 < 9 \times 10^{-1}\, P_{-2}^{7/4}\, a_{11}^{1/4}\, M_{1.4}^{-1/4}\, R_6^{-3}\, \nu_9^{1/2}\, f \quad \mathrm{G}\,, \tag{4}$$

where a_{11} is the orbital separation in units of 10^{11} cm, ν_9 is the radio frequency in GHz and $f \sim 1$ is a factor that depends on the stellar wind and binary parameters (for details see Kochanek 1993). Eq. (4) provides also a rough approximation to the condition that the dispersion measure is $\sim 1\ \mathrm{pc\,cm^{-3}}$ or less (cf. Eq. (2.4) in Kochanek 1993). Therefore, below the line corresponding to Eq. (4) in the $B - P$ diagram (see Fig. 1) a detectable radio pulsar signal is produced by a SXRT, if the other conditions described above are met.

If a radio pulsar is present, then the spin period evolution of the SXRT stage is determined by the competition of the spin-up resulting from accretion during the outbursts and the spin-down of the radio pulsar mechanism in the quiescent phases; the two effects balance each other for $B_9 \simeq 2\, P_{-2}^{7/4}\, L_{37}^{1/2}\, M_{1.4}^{-1/4}\, R_6^{-5/2}$ $\left(\Delta t_Q/\Delta t_O\right)_{100}^{-7/12}$ G, where L_{37} is the time-averaged outburst luminosity in units of $10^{37}\ \mathrm{erg\,s^{-1}}$ and $\left(\Delta t_Q/\Delta t_O\right)_{100}$ the ratio between the time spent in quiescence and the outburst duration in units of 100. SXRTs above the corresponding line in the $B - P$ diagram (see Fig. 1) would undergo secular spin-down, whereas a spin-up would characterize SXRTs below the line (Campana et al. 1993).

4. CONCLUSIONS

In this *Letter* we have shown that if an *accretion* powered luminosity of $\leq 10^{33} - 10^{34}\ \mathrm{erg\,s^{-1}}$ is a common characteristic of SXRTs after the end of an outburst or in quiescence, then two very different possibilities present themselves. If the "centrifugal barrier" is open, the accretion flow in quiescence extends to the surface of the neutron star and the energy liberated per unit mass is high. In this case, the accretion rates required to produce $10^{33} - 10^{34}\ \mathrm{erg\,s^{-1}}$ are so low that almost only neutron stars to the right of the "death line" would be able to accrete and therefore would not turn on as radio pulsars even if accretion stops completely (cf.

Fig. 1). The SXRT stage would then occur very early in the LMXRB phase or belong to a different evolutionary track.

If instead in the quiescent state the "centrifugal barrier" prevents the accreting matter from entering the neutron star magnetosphere, then a large region of the $B-P$ diagram would be available for the production of an observable radio pulsar signal, when the accretion flow becomes sufficiently low to be swept away. The low-level X-ray luminosity in quiescence does not provide any constraint in the $B-P$ diagram if it results from neutron star cooling.

Monitoring the X-ray luminosity of SXRTs in the decay from the outburst to the quiescent emission level could reveal the onset of the "centrifugal barrier" and provide further clues on the properties of the neutron stars in SXRTs. Prospects for observing a radio pulsar signal would be very promising if SXRTs with a minimum accretion luminosity at the neutron star surface of $\sim 10^{36} - 10^{37}$ erg s^{-1} were detected. In this case, not only the allowed radio pulsar spin-down luminosity could be 3–4 orders of magnitude higher, but a less pronounced variation of the mass inflow rate towards the neutron star magnetosphere would be required for the material to be swept away by the radio pulsar pressure.

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Figure caption

Fig. 1 Surface magnetic field plotted versus spin period of known pulsars (circles), taken from Taylor, Manchester & Lyne (1993). The "death line" (shadowed line) corresponds to the polar cap voltage below which the radio pulsar activity switches off. Solid lines represent the limit given by Eq. (1). Note that the line for $L = L_{\rm Edd} = 1.8 \times 10^{38}\, M_{1.4}$ erg s^{-1}, corresponds to the so called spin-up line. Dotted lines represent the limit given by Eq. (2). The dot-dashed line defines the condition $\tau_{ff} \sim 1$ (Eq. (4)) for the accretion rate given by Eq. (3). The dashed line separates the region in which the neutron star in a SXRT is expected to undergo secular spin-down (left) from that in which spin-up takes place (right).

Table 1: Minimum and quiescent luminosities of soft X-ray transients

Source	L_{min}^{obs} during outburst ($erg\,s^{-1}$; range $2-10$ keV)	Quiescent Luminosity ($erg\,s^{-1}$)	Outburst date(s) and Comments	References
MX 0656–07	$\sim 10^{36}\ d_{10}^2$		1975	Cominsky et al. 1978
MX 0836–42	$3 \times 10^{36}\ d_{10}^2$	$10^{35}\ d_{10}^2$ (1–2.4 keV)	1971/72 and 1990/91 – Burst	Cominsky et al. 1978; Belloni et al. 1993
Cen X-4	$3 \times 10^{35}\ d_{1.5}^2$	$\sim 10^{33}\ d_{1.5}^2$ (0.5–4.5 keV)	1969 and 1979 – Burst, $P_{orb} = 15$ h	van Paradijs et al. 1987
4U 1730–22	$3 \times 10^{36}\ d_{10}^2$		1972	Cominsky et al. 1978
KS 1731–260	$\sim 10^{37}\ d_{10}^2$		1989 – Burst	Sunyaev et al. 1990
A 1743–289	$2 \times 10^{36}\ d_{10}^2$		1975	Branduardi et al. 1976
A 1745–36	$\sim 2 \times 10^{36}\ d_{10}^2$		1976	Cominsky et al. 1978
MX 1746–20	$2 \times 10^{37}\ d_7^2$	$2 \times 10^{33}\ d_7^2$ (0.5–4.5 keV)	1971, in Globular cluster NGC 6440 ?	Cominsky et al. 1978; Hertz & Grindlay 1983
X 1803–245	$\sim 2 \times 10^{37}\ d_{10}^2$		1976	Jernigan et al. 1978
Aql X-1	$\sim 3 \times 10^{35}\ d_{2.5}^2$	$\sim 10^{34}\ d_{2.5}^2$ (1–10 keV)	Recurrent – Burst, $P_{orb} = 19\,h$, $P_{spin} = 131\,ms$?	Czerny et al. 1987