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# Constraints on the neutron star magnetic field of the two X-ray transients SAX J1808.4–3658 and Aql X–1

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**Abstract.** The recently discovered coherent X-ray pulsations at a frequency of ~400 Hz in SAX J1808.4–3658, together with a measure of the source luminosity in quiescence, allow us to put an upper limit on the neutron star magnetic field, that is $B \le 5 \times 10^8$ Gauss, using simple considerations on the position of the magnetospheric radius during quiescent periods. Combined with the lower limit inferred from the presence of X-ray pulsations, this constrains the SAX J1808.4–3658 neutron star magnetic field in the quite narrow range $(1-5) \times 10^8$ Gauss. Similar considerations applied to the case of Aql X–1 give a neutron star magnetic field lower than $\sim 10^9$ Gauss.

**Key words.** accretion disks – stars: individual: SAX J1808.4–3658, Aql X–1 – stars: neutron – X-rays: stars – X-rays: binaries – X-rays: general

## 1. Introduction

Low-mass X-ray binaries (LMXBs) consist of a neutron star, generally with a weak magnetic field ($B \lesssim 10^{10}$ Gauss), accreting matter from a low-mass ($\lesssim 1\ M_{\odot}$) companion. Neutron star soft X-ray transients (hereafter SXT) are a special subgroup of LMXBs. SXTs are usually found in a quiescent state, with luminosities in the range $10^{32}-10^{33}$ ergs/s. On occasions they exhibit outbursts, during which the luminosity increases to $\sim 10^{36}-10^{38}$ ergs/s and their behavior closely resemble that of persistent LMXBs. SXTs indeed form a rather inhomogeneous class, with sources showing regular outbursts (e.g. Aql X–1, Cen X–4, 4U 1608–522) and sources with long on/off activity periods (e.g. KS 1731–260, X 1732–304; see Campana et al. 1998 for a review).

The mechanism for the quiescent X-ray emission in these sources is still uncertain (e.g., Menou et al. 1999; Campana & Stella 2000; Bildsten & Rutledge 2001). The spectrum in quiescence is usually well fit by a soft thermal component (blackbody temperature of ~0.1–0.3 keV) plus a power-law component with a photon index $\Gamma \sim 1-2$. The blackbody component is interpreted as thermal emission from a pure hydrogen neutron-star atmosphere (e.g. Rutledge et al. 1999, 2000), while the power-law component is thought to be due to residual accretion or the interaction of a pulsar wind with matter released by the companion star (see e.g. Campana & Stella 2000, and references therein).

Some of these neutron star SXTs also show type-I X-ray bursts. During these bursts nearly-coherent oscillations are sometimes observed, the frequencies of which are in the rather narrow range between 300 and 600 Hz (see van der Klis 2000; Strohmayer 2001 for reviews). This frequency is interpreted as the neutron star rotation frequency (or twice this value), due to a hot spot (or spots) in an atmospheric layer of the rotating neutron star. Many LMXBs (including most of the SXTs) show rich time variability both at low and at high frequencies, in the form of noise components or quasi periodic oscillations (QPOs). In particular, QPOs at kilohertz frequencies (kHz QPOs), with frequencies ranging from a few hundred Hz up to 1200−1300 Hz (see van der Klis 2000 for a review), have been observed in the emission of about 20 LMXBs. Usually two kHz QPO peaks ("twin peaks") are simultaneously observed, the difference between their centroid frequencies being in the range 250–350 Hz (usually similar, but not exactly identical, to the corresponding nearly-coherent frequency of the burst oscillations, or half that value).

The presence and intensity of a magnetic field in LMXBs is an important question to address. The widely accepted scenario for the formation of millisecond radio pulsars is the recycling of an old neutron star by a spin-up process driven by accretion of matter and angular momentum from a Keplerian disc, fueled via Roche lobe overflow of a binary late-type

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companion (see Bhattacharya & van den Heuvel 1991 for a review). Once the accretion and spin-up process ends, the neutron star is visible as a millisecond radio pulsar. The connection between LMXBs and millisecond radio pulsars indicates that neutron stars in LMXBs have magnetic fields of the order of $B \sim 10^8 - 10^9$ Gauss. In this case, the accretion disc in LMXBs should be truncated at the magnetosphere, where the disc pressure is balanced by the magnetic pressure exerted by the neutron star magnetic field. Although widely accepted, there is no direct evidence confirming this scenario yet. However, the discovery of coherent X-ray pulsations at ∼2.5 ms in SAX J1808.4–3658 (a transient LMXB with an orbital period $P_{\rm orb} = 2$ h, Wijnands & van der Klis 1998) has proved that the neutron star in a LMXB can be accelerated to millisecond periods. Recently, other two transient LMXBs have been discovered to be millisecond X-ray pulsars, namely XTE J1751–305 ($P_{\rm spin} \sim 2.3$ ms, $P_{\rm orb} = 42$ min, Markwardt et al. 2002) and XTE J0929–314 ($P_{\rm spin} \sim 5.4$ ms, $P_{\rm orb} = 43$ min, Galloway et al. 2002).

Although there are indications for the presence of a (weak) magnetic field in LMXBs, it is not clear yet whether this magnetic field plays a role in the accretion process onto the neutron star. If the neutron stars in LMXBs have magnetic fields and spin rates similar to those of millisecond radio pulsars (as implied by the recycling scenario), then the accretion disk should be truncated quite far (depending on the accretion rate) from the stellar surface, and the magnetic field should affect the accretion process. However, the similarity in the spectral and timing behavior between LMXBs containing neutron stars and black hole binaries (see Di Salvo & Stella 2002; van der Klis 2000 for reviews) suggests that the neutron star magnetic field is so weak (less than $10^8$ Gauss, Kluzniak 1998) that it plays no dynamical role, and the disk is truncated quite close to the marginally stable orbit, both in neutron star and in black hole systems.

We have proposed a method to constrain the magnetic field of transient LMXBs containing neutron stars based on their measured luminosity in quiescence and spin rates (when available, Burderi et al. 2002a). In this paper we apply this method to some SXTs for which the luminosity in quiescence and the spin period are known.

## 2. Constraints on the neutron star magnetic field from the quiescent X-ray luminosity

Burderi et al. (2002a) have shown that it is possible to derive an upper limit on the neutron star magnetic field measuring the luminosity of these sources in quiescence and comparing it with the expectations from the different mechanisms that have been proposed to explain the quiescent X-ray emission of neutron star SXTs. In the following we will summarize their conclusions. There exist three sources of energy which might produce some X-ray luminosity in quiescence (see also Stella et al. 1994):

a) Residual accretion onto the neutron star surface at very low rate (e.g. Stella et al. 1994);
b) Rotational energy of the neutron star converted into radiation through the emission from a rotating magnetic dipole, a fraction of which can be emitted in X-rays (e.g. Possenti et al. 2002; Campana et al. 1998b, and references therein);
c) Thermal energy, stored into the neutron star during previous phases of accretion, released during quiescence (e.g. Brown et al. 1998; Colpi et al. 2001; Rutledge et al. 2001).

Constraints on the neutron star magnetic field can be derived considering processes a and b, in the hypothesis that the neutron star spin frequency is known. Note that, while processes a and b are mutually exclusive, process c will probably always contribute to the luminosity in quiescence, reducing the amount of emission due to one of the first two processes.

If the neutron star has a non-zero magnetic field, then its magnetospheric radius can only be inside or outside the light-cylinder radius (i.e. the radius at which an object corotating with the neutron star, having spin period $P$, attains the speed of light $c$, $r_{\rm LC} = cP/2\pi$), with different consequences on the neutron star behavior.

If the magnetospheric radius is inside the light cylinder radius, scenario a, there should be some matter flow inside the light cylinder radius in order to keep the magnetospheric radius small enough. Actually, accretion onto a spinning, magnetized neutron star is centrifugally inhibited once the magnetospheric radius is outside the corotation radius, i.e. the radius at which the Keplerian frequency of the orbiting matter is equal to the neutron star spin frequency, $r_{\rm co} = 1.5 \times 10^6 P_{-3}^{2/3} m^{1/3}$ cm (where $P_{-3}$ is the spin period in ms and $m$ is the neutron star mass in solar masses, $M_\odot$). In this scenario we have therefore two possibilities: a1) the magnetospheric radius is inside the co-rotation radius, so accretion onto the neutron star surface is possible; a2) the magnetospheric radius is outside the co-rotation radius (but still inside the light cylinder radius), so the accretion onto the neutron star is centrifugally inhibited, but an accretion disk can still be present outside $r_{\rm co}$ and emit X-rays.

If the magnetospheric radius falls outside the light-cylinder radius, it will also be outside the corotation radius. This means that the space surrounding the neutron star will be free of matter up to the light cylinder radius. It has been demonstrated that a rotating magnetic dipole in vacuum emits electromagnetic dipole radiation according to the Larmor's formula, and a wind of relativistic particles associated with magnetospheric currents along the field lines is expected to arise (e.g. Goldreich & Julian 1969). Therefore, the neutron star is expected to emit as a radio pulsar. In this case X-ray emission can be produced by: b1) reprocessing of part of the bolometric luminosity of the rotating neutron star into X-rays in a shock front between the relativistic pulsar wind and the circumstellar matter; b2) the intrinsic emission in X-rays of the radio pulsar.

In all these scenarios we have calculated the expected X-ray luminosity in quiescence, which of course depends on the neutron star spin frequency and magnetic field (see Burderi et al. 2002a, and references therein, for details). This can be compared with the observed quiescent luminosity (which has to be considered as an upper limit for the luminosity due to each of these processes, given that process c is also expected to contribute) giving an upper limit on the magnetic field, once the neutron star spin frequency is known. For each of the scenarios above, these upper limits are:

a1) $\mu_{26} \leq 0.08 L_{33}^{1/2} m^{1/3} P_{-3}^{7/6}$

a2) $\mu_{26} \leq 1.9 L_{33}^{1/2} m^{-1/4} P_{-3}^{9/4}$

b1) $\mu_{26} \leq 0.05 L_{33}^{1/2} P_{-3}^{2} \eta^{-1/2}$

b2) $\mu_{26} \leq 2.37 L_{33}^{0.38} P_{-3}^{2}$

where $\mu_{26}$ is the neutron star magnetic moment in units of $10^{26}$ Gauss cm$^3$, $L_{33}$ is the accretion luminosity in units of $10^{33}$ ergs/s, and $\eta \sim 0.01$–$0.1$ is the efficiency in the conversion of the rotational energy into X-rays (e.g. Campana et al. 1998b; Tavani 1991; Kaspi et al. 1995; Grove et al. 1995). Note that the values assumed for $\eta$ are quite uncertain given that they are inferred from radio pulsar studies and, of course, depend on the geometry of the system as well as on the characteristics of the surrounding environment. However, these values are also in agreement with the measured quiescent X-ray emission of SXTs (Campana et al. 1998b).

We have already applied this considerations to the case of KS 1731–260, getting valuable results (Burderi et al. 2002a). In the following we re-calculate the upper limit on the neutron star magnetic field of this source using the most recent measurement of its quiescence luminosity obtained from XMM-Newton observations (Wijnands et al. 2002).

KS 1731–260 is a neutron star SXT, which in February 2001 entered a quiescent state after a long period of activity lasted more than a decade. The quiescent X-ray luminosity of $\sim 10^{33}$ ergs/s was measured with Chandra (Wijnands et al. 2001) and BeppoSAX (Burderi et al. 2002a). The X-ray spectrum obtained with Chandra is well described by a blackbody at a temperature of $\sim$0.3 keV (Wijnands et al. 2001) or by a hydrogen atmosphere model, obtaining an effective temperature of 0.12 keV and an emission area radius of $\sim$10 km (Rutledge et al. 2001). KS 1731–260 also shows nearly-coherent burst oscillations at $\sim$524 Hz (corresponding to a period of 1.91 ms, which is most probably the neutron star spin period, see Muno et al. 2000). A recent XMM-newton observation of this source gave a quiescent luminosity of $\sim(2$–$5) \times 10^{32}$ ergs/s, about a factor of two lower than the previous BeppoSAX and Chandra estimations. Adopting therefore a quiescent luminosity of $5 \times 10^{32}$ ergs/s and a spin period of 1.9 ms, the upper limits to the magnetic field of the neutron star in KS 1731–260 are: a1) $\mu_{26} \leq 0.2 P_{1.9}^{7/6} \mathrm{m}^{1/3}$; a2) $\mu_{26} \leq 5.9 P_{1.9}^{9/4} \mathrm{m}^{-1/4}$; b1) $\mu_{26} \leq 1.3 P_{1.9}^{2} \eta_{0.01}^{-1/2}$; b2) $\mu_{26} \leq 6.6 P_{1.9}^{2}$. Here $P_{1.9}$ is the spin period in units of 1.9 ms, and $\eta_{0.01}$ is the conversion efficiency $\eta$ in units of 0.01. In any case the magnetic field of KS 1731–260 results most probably less than $\sim 7 \times 10^8$ Gauss.

## 3. Constraints on the magnetic field of SAX J1808.4–3658 and Aql X–1

SAX J1808.4–3658, another bursting SXT, was the first (low magnetized) LMXB to show coherent pulsations, at a frequency of $\sim$401 Hz, in its persistent emission (Wijnands & van der Klis 1998), thus providing the first direct evidence of the current evolutionary scenarios according to which LMXBs are the progenitors of millisecond radio pulsars. SAX J1808.4–3658 has been observed in quiescence with XMM: the 0.5–10 keV unabsorbed luminosity was $5 \times 10^{31}$ ergs/s (Campana et al. 2002). Using the reasoning described above we can calculate the upper limits on the neutron star magnetic field in this system, which for the various processes are respectively: a1) accretion: $\mu_{26} < 0.054\, \mathrm{m}^{1/3}$; a2) propeller: $\mu_{26} < 3.4\, \mathrm{m}^{-1/4}$; b1) reprocessed radio emission: $\mu_{26} < 0.71 \eta_{0.01}^{-1/2}$; b2) radio pulsar emission: $\mu_{26} < 4.69$. In this case we find a maximum neutron star magnetic field strength of $\sim 4.7 \times 10^8$ Gauss. A lower limit on the pulsar magnetic field in SAX J1808.4–3658 was calculated using the observation of coherent pulsations during the 1998 outburst, i.e. imposing that the magnetospheric radius is larger than the neutron star radius at the highest flux level; this gives $B \geq 1 \times 10^8$ Gauss (Psaltis & Chakrabarty 1999). Combining this with our upper limit, we can constrain the neutron star magnetic field in this system in the rather small range $(1$–$5) \times 10^8$ Gauss. Note that the presence of coherent pulsations in this source excludes the possibility that the magnetic field is as weak as $\sim$0.05 Gauss; therefore the residual accretion (scenario a1) is excluded in this case. This has important consequences as regards the understanding of the origin of the quiescent emission. In the case of SAX J1808.4–3658 the X-ray spectrum in quiescence is dominated by the power-law component; the soft blackbody component (if any) contributes at least a factor of 15 less than the power law to the quiescent luminosity in the 0.5–10 keV range (see Campana et al. 2002). Although the details of the emission in the propeller regime are not clear, we would expect that in this regime the source spectrum is dominated by a thermal component from the residual accretion disk that should be present outside the magnetospheric radius. This is not the case for SAX J1808.4–3658. Therefore we suggest that while its thermal (blackbody) component is most probably due to what we called process c, i.e. cooling of the neutron star heated during the previous accretion phase, its non-thermal (power-law) component, which sometimes constitutes most of the quiescent emission, is most probably due to dipole emission from the radio pulsar (scenarios b1 and/or b2). Note, however, that recent observational results on the variability of the soft component during a quiescence period of Aql X–1 pose some problems to the neutron star cooling scenario (see Rutledge et al. 2002).

Aql X–1 is a SXT showing type-I X-ray bursts. Based on RXTE/PCA observations taken during an outburst in 1997, Zhang et al. (1998) discovered nearly coherent oscillations with an asymptotic frequency of 548.9 Hz (corresponding to a period of 1.82 ms) during the decay of a type I X-ray burst. This signal, as well as similar signals observed during type I X-ray bursts from about ten low mass X-ray binaries, likely corresponds to the neutron star rotation frequency (or twice its value; for a review see Strohmayer 2001). Aql X–1 also shows kHz QPOs: the lower peak frequency varies in the range 670−930 Hz, while the upper peak was only marginally detected at $\sim$1040 Hz (see van der Klis 2000 and references therein). The peak separation between the kHz QPOs is

241±9 Hz, inconsistent with (but close to) half the frequency of the burst oscillations. We will therefore assume that the neutron star in this system is spinning at a period of 1.82 ms or 3.64 ms. Note, however, that the lack of harmonic content in the burst oscillations (see Muno et al. 2002) might suggest that these correspond indeed to the neutron star spin frequency. Aql X–1 was observed several times in quiescence (with ROSAT, Verbunt et al. 1994; ASCA, Asai et al. 1998; BeppoSAX, Campana et al. 1998; and Chandra, Rutledge et al. 2001). For the quiescent X-ray luminosity of Aql X–1 we adopt the minimum value reported in the literature, that is $\sim 1.6 \times 10^{33}$ ergs/s (from Verbunt et al. 1994, extrapolated in the 0.5–10 keV energy range and recomputed for a distance of 5 kpc, see Rutledge et al. 2002). Using these parameters we can apply the formulas above to calculate the upper limit on the neutron star magnetic field in Aql X–1: a1) accretion: $\mu_{26} < 0.20 P_{1.8}^{7/6} \mathrm{m}^{1/3}$; a2) propeller: $\mu_{26} < 9.25 P_{1.8}^{9/4} \mathrm{m}^{-1/4}$; b1) reprocessed radio emission: $\mu_{26} < 2.1 P_{1.8}^{2} \eta_{0.01}^{-1/2}$; b2) radio pulsar emission: $\mu_{26} < 7.85 P_{1.8}^{2}$. Here $P_{1.8}$ is the spin period in units of 1.8 ms. For a spin period of 1.82 ms, the highest magnetic field we get is $\sim 9 \times 10^{8}$ Gauss. Assuming a spin period of 3.64 ms, the magnetic field is less constrained, with a maximum value of $\sim 4 \times 10^{9}$ Gauss that is obtained in the propeller (a2) scenario (note that much lower upper limits are obtained in the case of residual accretion, a1, and reprocessed radio emission, b2).

## 4. Discussion and conclusions

We have applied a method to constrain the magnetic field of transient LMXBs containing neutron stars based on their measured luminosity in quiescence and spin rates. This gives a magnetic field lower than $\sim 7 \times 10^{8}$ Gauss for KS 1731–260 and lower than $\sim 10^{9}$ Gauss for Aql X–1, and constrains the magnetic field of the millisecond X-ray pulsar SAX J1808.4–3658 in the quite narrow range between $10^{8}$ and $5 \times 10^{8}$ Gauss.

In the case of SAX J1808.4–3658 we also find that residual accretion onto the neutron star very unlikely contributes to the source luminosity in quiescence, and we suggest that the non-thermal (power-law) component of the source spectrum in quiescence is probably produced by reprocessed and/or direct dipole emission from the radio pulsar, which may switch on at very-low accretion rates. In the arguments developed above we assume that, once the accretion rate significantly decreases during quiescence, the radio pulsar switches on when the magnetospheric radius becomes larger than the light cylinder radius. In this case, we can estimate the timescale on which the pulsar is expected to clean the space up to its light cylinder radius and turn on, which of course will depend on the details of the decrease in the mass accretion rate. Assuming that the mass accretion rate instantaneously drops to a very low value, we have estimated the net force on the disk (considered in the standard Shakura & Sunyaev 1973, configuration) induced by the magnetic field pressure. This rough calculation gives a timescale of $\sim 1-10$ s (depending on the residual accretion rate and on the viscosity parameter $\alpha$) in the case of SAX J1808.4–3658.

However, more evidences are needed to confirm this suggestion, as, for instance, the detection of pulsed radio emission in quiescence. Indeed, despite thoroughly searched in radio during its X-ray quiescent phase, no pulsed radio emission has been detected from SAX J1808.4-3658 up to now (see e.g. Burgay et al. 2002). This can be caused by the presence of a strong wind of matter emanating from the system: the mass released by the companion star swept away by the radiation pressure of the pulsar, as predicted in the so-called radio-ejection model (Burderi et al. 2001, see also Burderi et al. 2002b). This means that SAX J1808.4-3658 may show radio pulsations in quiescence when observed at frequencies higher than the standard 1.4 GHz (the frequency at which radio pulsars are normally searched), where the free-free absorption is less severe.

We note, however, that our magnetic field upper limits are subject to significant uncertainties (that will be probably addressed by future studies) due to our lack of understanding of the structure of the accretion flow in quiescence. In particular, our calculations consider an accretion-disk geometry. In a different geometry, it is not clear whether a distinction between the residual accretion scenario and the propeller scenario can be made. Menou et al. (1999) have presented a propeller scenario that still allows for partial residual accretion if accretion in quiescent neutron star SXTs occurs via a quasi-spherical Advection Dominated Accretion Flow (ADAF), rather than a thin disk. This allows some material to accrete near the poles, bypassing the centrifugal barrier (see also Zhang et al. 1998). However, only a very small fraction (if any) of the total accretion rate in quiescence is expected to accrete onto the neutron star surface (Menou et al. 1999), consistently with the fact that no coherent pulsations are detected during quiescence. Other significant uncertainties are in the assumed values of the efficiency $\eta$ in the conversion of the pulsar spin-down energy into X-rays in the shock front, b1, scenario and in the fraction of the intrinsic radio-pulsar emission emitted in X-rays (scenario b2).

Although subject to some uncertainties our upper limits on the neutron star magnetic field are reasonable and in agreement with limits found from different considerations. The presence of a weak, but not negligible, magnetic field in LMXBs has been invoked to explain some observational facts such as the QPO at $\sim 20-60$ Hz (the so-called low-frequency QPO in atoll sources or horizontal branch oscillations, HBOs, in Z sources; Psaltis et al. 1999), or the disappearance of the kHz QPOs at low and high inferred mass accretion rates (e.g. Campana 2000; Cui 2000). In particular, linking the kHz QPO observability to variations of the neutron star magnetospheric radius, in response to changes in the mass accretion rate, Campana (2000) estimates a magnetic field of $B \sim (0.3-1) \times 10^{8}$ Gauss for Aql X-1 and of $B \sim (1-8) \times 10^{8}$ Gauss for Cyg X-2. A method for determining the $B$-field around neutron stars based on observed kilohertz and other QPOs frequencies, in the framework of the transition layer QPO model (Titarchuk et al. 1998), gives dipole fields with the strengths of $10^{7}-10^{8}$ Gauss on the neutron star surface for 4U 1728–34, GX 340+0, and Scorpius X-1 (Titarchuk et al. 2001).

The accurate measurement of the luminosity in quiescence of other SXTs (and in particular of the other X-ray millisecond pulsars, for which the spin period is precisely determined), certainly possible with the high sensitivity of the instruments on board Chandra and XMM-Newton, will give important information about the magnetic field in these systems and therefore about the connection between the populations of LMXBs and millisecond radio pulsars as well as about the influence of the magnetic field in the accretion process onto the neutron star.

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