Could AX J1841.0–0536 be an anti-magnetar?

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ABSTRACT

Recent observations show that supergiant fast X-ray transients (SFXTs) spend most of their lifetime at an intermediate level luminosity of $\sim 10^{33}–10^{34}$ erg$^{-1}$, and, when a blackbody model for the spectra is adopted, the resulting radii of the emission region are always only a few hundred metres, supporting the idea that during the intermediate state SFXTs are accreting matter from the companion star. From these observational phenomena we derive possible constraints on the magnetic field strengths of the neutron stars in four SFXTs with known spin periods. While IGR J11215–5952, IGR J16465–4507 and IGR J18483–0311 may have magnetic fields (up to a few $10^{11}–10^{12}$ G) similar to those of normal X-ray pulsars, the magnetic field of AX J1841.0–0536 is considerably low ($\lesssim 10^7$ G). The high-mass companion stars in SFXTs imply that the neutron stars are relatively young objects, with age less than $\sim 10^7$ yr. Analysis of the spin evolution shows that neutron stars like AX J1841.0–0536 should be born with relatively long spin periods ($\gtrsim 1$ s). Considering the fact that among the four SFXTs only AX J1841.0–0536 is a ‘proper’ one, and the other three are either ‘intermediate’ SFXTs or have peculiar characteristics, we suggest that the neutron stars in some of the SFXTs may have similar characteristics as several young central compact objects in supernova remnants called ‘anti-magnetars’. These features, combining with accretion from clumpy winds, could make them distinct from standard supergiant X-ray binaries – the low fields and relatively long spin periods guarantee accretion at a very low level, resulting in a large dynamic range ($10^5–10^5$) of X-ray luminosity.

Key words: stars: neutron – X-rays: binaries – X-rays: individual: IGR J11215–5952 – X-rays: individual: IGR J16465–4507 – X-rays: individual: IGR J18483–0311 – X-rays: individual: AX J1841.0–0536.

1 INTRODUCTION

Most of the high-mass X-ray binaries (HMXBs) consist of a neutron star (NS) accreting from its high-mass companion star, usually of O or B type. They are traditionally divided into two types, in which either a supergiant star or a Be star is contained, and the X-ray source often is a pulsar. In the supergiant systems, accretion onto the compact star occurs via capture of the stellar wind or Roche lobe overflow from the companion star, while in the Be systems only wind accretion takes place, since the Be star is well inside its Roche lobe (see Tauris & van den Heuvel 2006, for a review). In recent years, a new type of HMXBs was discovered by INTEGRAL, called supergiant fast X-ray transients (SFXTs; see e.g. Sidoli 2011, for a recent review). These sources are characterized by X-ray outbursts composed of short bright flares up to peak luminosities of $\sim 10^{37}–10^{37}$ erg$^{-1}$, with the duration of a few hours for each single flare. In quiescence, the luminosity is as low as $10^{32}$ erg$^{-1}$, so that the dynamic range of X-ray luminosity reaches 4–5 orders of magnitude. X-ray pulsations have been detected in a few sources, leading to the firm identification of the compact object as an NS. This is also supported by their hard X-ray spectra, which are represented by flat hard power law below 10 keV with high energy cut-off at about 15–30 keV, sometimes strongly absorbed at soft energies, similar as in X-ray pulsars (Sidoli, Paizis & Mereghetti 2006; Walter et al. 2006; Romano & Sidoli 2010).

Models for SFXTs can be roughly divided into three categories, though none of them can be responsible for all the observational properties. The most widely studied one is the clumpy wind model, which invokes the idea that the supergiant winds are strongly inhomogeneous rather than smooth (Oskinova, Hamann & Feldmeier 2008), with large density contrasts ($\sim 10^5–10^9$). The short flares in SFXTs are suggested to be produced by the accretion of massive clumps ($10^{22}–10^{23}$ g) in the winds (in’t Zand 2005; Walter & Zurita Heras 2007; Negueruela et al. 2008). Between the clumps the accretion rate is very low, and the sources become dim. The clumps are expected to be small and crowded near the surface of the supergiant and become large and sparse when the wind blows out. As a result,
in the region within $2R_\star$ (where $R_\star$ is the radius of the supergiant),
the clumpy wind can be treated as roughly homogeneous and continuous,
while outside the region, the effect of clumping becomes important (Negueruela
et al. 2008). In this model, the SFXTs should display wider and more eccentric
orbits than persistent HMXBs.

The regular 329.4 outbursts and longer outburst duration, as well as
the narrow and steep light curve in IGR J11215–5952 suggest
the presence of an inclined equatorial wind component in
this system, which is denser and slower than the symmetric po-
lar wind from the blue supergiant (Sidoli et al. 2007). This model
requires the outbursts to be periodical or semi-periodical. Besides
IGR J11215–5952, IGR J18483–0311 also displays periodically
recurrent outbursts (Sidoli et al. 2009b), suggesting that the outburst
is triggered near the periastron passage in a highly eccentric orbit.

The gated models (Grebenev & Sunyaev 2007; Bozzo, Falanga
& Stella 2008) are based on the analysis of a different stage of the
NS’ spin evolution in the wind environment by comparing the accre-
tion radius $R_a$, the magnetospheric radius $R_m$ and the corotation
radius $R_{co}$. Transitions across these stages may lead to large varia-
tions in the X-ray luminosity with relatively small changes in the
mass accretion rate. If some of the SFXTs have long spin periods
($\gtrsim 1000$ s), this model implies large magnetic fields ($\gtrsim 10^{13}–10^{15}$ G)
for the NSs in the cases of the centrifugal and magnetic barriers.

Recent observations with Swift, Suzaku and XMM–Newton have
revealed some new features of SFXTs (e.g. Romano et al. 2008;
Sidoli et al. 2008, 2009a, 2010a; Giunta et al. 2009; Romano, Sidoli
& Cusumano 2009a,b; Bozzo et al. 2010; Romano, Sidoli &ucci
2010; Bodaghee et al. 2011; Romano et al. 2011). One of the most
prominent results is that SFXTs spend most of their life still accre-
ting matter even outside bright flaring activity rather in quiescence,
emitting at an intermediate level luminosity of $\sim 10^{33}–10^{34}$ erg s$^{-1}$
with hard X-ray spectra. Especially, spectral analyses of the X-ray
emission in the intermediate state show that, when a blackbody
model is adopted, the resulting radii of the emission region are al-
ways only a few hundred metres, clearly associated with the polar
caps of the NSs. These results strongly support the fact that the intermediate (and probably very low) intensity emission of SFXTs
is produced by the accretion of matter on to the NSs. In the fol-
lowing section, we will use these facts to constrain the magnetic
field strengths of several NSs in SFXTs. We discuss their possible
implications in Section 3 and conclude in Section 4.

2 POSSIBLE CONSTRAINTS ON NS MAGNETIC FIELD STRENGTHS

Davies & Pringle (1981) argued that, when captured by an NS in
HMXBs, the wind material from the optical companion star always
forms a quasi-static envelope surrounding the NS. The interaction
between the NS and the wind material leads to different evolutionary
stages of the NS, i.e. (a) pulsar phase, (b) rapid rotator phase, (c)
supersonic propeller phase and (d) subsonic propeller phase. It is
not clear whether phase (d) exists in a realistic situation (see also
the discussion below). Due to the short duration and weak radiation,
it is difficult to be testified by either observations or numerical
simulations. Population synthesis calculations by Dai & Li (2006)
showed that the relation between the orbital periods and the spin
periods of wind-fed X-ray pulsars in supergiant HMXBs can be
roughly accounted without requiring that an X-ray pulsar emerges
when passing phase (d). Nevertheless, the end of phase (c) can be
taken as a conservative condition for the occurrence of accretion
on to the polar cap region of the NS. The observational evidence of accretion on to the NS in SFXTs during the intermediate state
may help draw useful constraints on the magnetic fields of the NSs.
In the following, we use $M$, $M_\star$, $B$, $R$ and $P_\star$ to denote the mass,
mass accretion rate, magnetic field, radius and spin period of the NS, respectively.

(1) If steady accretion occurs during the intermediate state, one
possible implication is that the plasma at the base of the NS magne-
tosphere has become sufficiently cool, so that the magnetospheric boundary is unstable with respect to interchange instabilities (e.g. Rayleigh–Taylor instability or RTI; Arons & Lea 1976; Elsner & Lomb 1977). This can be realized only if the cooling processes in the envelope are effective and the spin period of the star exceeds a so-
called break period $P_{br}$ (Davies & Pringle 1981; Ikhsanov 2001a),
which denotes the end of phase (d),

$$P_\star \gtrsim P_{br} \sim 1.2 \times 10^4 B_{12}^{16/21} M_{13}^{-5/7} M_{15}^{-1/21} R_6^{16/7} \text{s},$$

(1)

where $B_{12} = B/10^{12}$, $R_6 = R/10^6$ cm, $M_{13} = M/10^{13}$ g and $M_1 = M/\mathcal{M}_\odot$; Arons & Lea (1976) and Elsner & Lomb (1977)
also showed that for the conditions of interest the magnetospheric boundary can be interchanged unstably only if the Compton
cooling is effective. This gives the following condition on the X-ray
luminosity:

$$L_X \gtrsim L_{cr} \sim 3 \times 10^{36} B_{12}^{1/4} M_{15}^{1/2} R_6^{-1/8} \text{erg s}^{-1}.$$  

(2)

Obviously, the luminosity given by equation (2) is too high for
the intermediate state luminosities ($\sim 10^{33}–10^{34}$ erg s$^{-1}$) of SFXTs,
unless the magnetic fields are extremely (and unrealistically) low.
Thus, we are led to the conclusion that the X-ray emission during the intermediate state is unlikely due to accretion driven by interchange
instabilities.

The calculations by Arons & Lea (1976) and Elsner & Lamb (1977) were all performed by assuming a non-rotating NS. This
is a reasonable approximation in the case of very slowly rotating
objects. Burnard, Lea & Arons (1983) showed that different conditions
might apply if the rotation of the NS is taken into account. In
this case, even if the RTI is suppressed, the accreting matter
can still penetrate through the star’s magnetic field lines due to a
shearing instability (Kelvin–Helmholtz instability, or KHI). This
means that a relatively large amount of matter can accrete on to
the NS even if the RTI is not at work. Thus, we first take the simplest
assumption that direct accretion occurs with the help of KHI if the
magnetospheric radius of the NS,

$$R_m = \left( \frac{B^2 R^4}{M \sqrt{2GM}} \right)^{2/7},$$

(3)
is smaller than the corotation radius

$$R_{co} = \left( \frac{GM}{4\pi \rho_\star^2} \right)^{1/3},$$

(4)

where $G$ is the gravitational constant. Equivalently, the NS has
evolved beyond phase (c) and its spin period is longer than the
equilibrium period:

$$P \gtrsim P_{eq} \sim 165.5 B_{12}^{6/7} M_{13}^{-3/7} M_{15}^{-5/7} R_6^{18/7} \text{s}.$$  

(5)

This condition sets the maximum of the magnetic field strength of the NS as

$$B_{12,\max} \sim 0.085 \left( \frac{P_\star}{20\text{s}} \right)^{7/6} M_{13}^{1/2} M_{15}^{-5/6} R_6^{-3/5}.$$  

(6)

(2) The above derivations are based on the assumption that there
is direct accretion during the intermediate state. This may apply for,
e.g., the clumpy wind model. In the gated model, however, even if the
magnetospheric boundary is stable against RTI or KHI, in the

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subsonic propeller phase (d), part of the plasma at the base of the NS magnetosphere may penetrate into the magnetosphere and flow along the field lines to the polar caps due to turbulent diffusion and reconnection of the magnetic field lines, as suggested by Ikhsanov (2001b) and Bozzo et al. (2008). Ikhsanov (2001b) showed that the rate of plasma penetration due to magnetic line reconnection is about 1 per cent of the mass capture rate $\dot{M}_\bullet$, when the efficiency of the reconnection process $\eta \sim 0.1$, and the average scale of plasma vortices of the embedded field is $\lambda_m \sim 0.1 R_\bullet$. The rate of diffusion is generally lower than that of line reconnection by more than two orders of magnitude and is not considered here. Roughly speaking, to produce X-ray emission with the luminosity of $10^{32}$–$10^{38}$ erg s$^{-1}$ in phase (d), the mass capture rate has to be $\dot{M}_\bullet \sim 10^{15}$–$10^{16}$ g s$^{-1}$. However, the big uncertainties in the introduced parameters ($\alpha$, and $\lambda_m$) prevent a reliable estimate of the mass capture rates from observed luminosities. On the other hand, if the intermediate level X-ray luminosities are really produced by field penetration in phase (d), then we can safely derive that, during outbursts direct accretion must take place, i.e. the NS spin period must be longer than the corresponding break period. Taking $\dot{M}_\bullet \sim 10^{16}$ g s$^{-1}$ as a typical mass accretion rate during outbursts, we can estimate the maximum of the field strength from equation (1)

$$B_{12,\text{max}} \approx 0.15 \left( \frac{P}{20\text{s}} \right)^{1/16} \frac{3^{1/16} M_{15}^{1/4} M_{10}^{1/4}}{R_6^3}. \quad (7)$$

Alternatively, equation (2) presents another upper limit of the field strength with $L_X \sim 10^{36}$ erg s$^{-1}$,

$$B_{12,\text{max}} \approx 1.2 \times 10^{-2} L_{X,36}^{1/2} M_{10}^{1/2} R_6^-,$$  

where $L_{X,36} = L_X/10^{36}$ erg s$^{-1}$. However, since $L_X$ is quite insensitive to $B$ (see equation 2), this may lead to large uncertainty in estimating $B$ from the observed $L_X$. So in the following we will not consider the result from equation (8).

Currently, there are about 10 confirmed SFXTs, among which only four have spin periods detected (Sidoli 2011, and references therein). In Table 1, we list their orbital and spin periods ($P_{\text{orb}}$ and $P_s$). In column 4, we also present their X-ray luminosities (in units of $10^{33}$ erg s$^{-1}$) in the intermediate state, or the minimum X-ray luminosities, for which spectral information was available. The maximum field strengths, derived from equations (6) and (7), are shown in columns 5 and 6, respectively. Here we relate the X-ray luminosity to the accretion rate via the formula $L_X = G M M/R$ and adopt the NS mass $M = 1.4 M_\odot$ and radius $R = 10^6$ cm.

From Table 1, we find interesting distributions of the NS magnetic fields. IGR J11215–5952, IGR J16465–4507 and IGR J18483–0311 may have relatively high magnetic fields (a few $10^{10}$–$10^{12}$ G), comparable with those of typical HMXBs, while the magnetic field of AX J1841.0–0536 is considerably low ($\lesssim 10^{10}$ G).

We note that IGR J11215–5952 is actually a peculiar SFXT, since it is the only one so far showing strictly periodic outbursts (Sidoli et al. 2007). Both IGR J16465–4507 and IGR J18483–0311 are classified as ‘intermediate’ SFXTs (Walter & Zurita Heras 2007; Romano et al. 2010, see also Clark et al. 2010; La Parola et al. 2010), since the variations of their X-ray fluxes are significantly lower than that observed from the SFXT prototypes ($\sim 10^{8}$–$10^{9}$). Hence it seems that only AX J1841.0–0536 is a ‘proper’ SFXT. Besides this source, lines of possible evidence for low-field NSs in SFXTs were also noted in Sguera et al. (2010) and Grebenev (2010).

(3) Another possible estimate of the magnetic fields can be obtained from the size $S$ of the polar caps during accretion (Frank, K. & Raine 2002),

$$S \sim \pi R_p^2 = \pi (R/R_\bullet) R^2 \sin^2 \alpha,$$  

where $R_{\text{pc}}$ and $\alpha$ are the radius of the polar cap and the angle between the magnetic axis and the equatorial plane, respectively. Equation (9) yields the maximum of the magnetospheric radius if $R_{\text{pc}}$ is known,

$$R_{\text{pc}} \lesssim (R/R_\bullet)^2 R.$$  

Combining equations (3) and (10) and taking $R_{\text{pc}} \sim 0.25$ km and $M \sim 10^{13}$ g s$^{-1}$ (e.g. Romano et al. 2010), we always have $B_{12} \lesssim 0.1$, which seems to be independent of the models of accretion modes of NSs. However, one should take caution when adopting this result, since other spectral models (e.g. absorbed power law, sometimes with high-energy cut-off) also well fit the data during the intermediate and low states. Additionally, Bozzo et al. (2010, see also Bodaghee et al. 2011) pointed out that models describing spherical accretion on to magnetized NSs predict an inverse relation between the size of the hotspot and $L_X^{1/2}$, at least for systems with $L_X < 10^{35}$ erg s$^{-1}$ (White, Swank & Holt 1983). This seems to be in contrast with the observed relation that the blackbody radius grows with the X-ray intensity (Romano et al. 2009a).

The above estimates suggest that the NSs in some SFXTs could have relatively low fields ($\lesssim$ a few $10^{10}$–$10^{12}$ G). This distinct feature may differentiate them from normal supergiant HMXBs. Because of their low magnetic fields, they are able to accrete at a very low rate, resulting in a large dynamic range of X-ray luminosities. We note that recent XMM–Newton observations of IGR J18483–0311 showed evidence of an emission line feature at $\sim 3.3$ keV in the 0.5–10 keV spectrum, implying an NS magnetic field of $\sim 3 \times 10^{11}$ G if it could be ascribed to an electron cyclotron emission line (Sguera et al. 2011). However, we need to emphasize that in deriving both equations (6) and (7) we have assumed a dipolar magnetic field for the NSs, neglecting possible multipolar structures. Additionally, the deviation of the NS radius from $10^6$ cm may considerably influence the estimate of the field strengths.

3 CONSTRAINTS ON THE INITIAL SPIN PERIODS

If part of the SFXTs are relatively low-field objects, it is interesting to see how they have evolved to the current spin periods. NSs

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**Table 1.** Observed and derived parameters of four (possible) SFXTs.

| Source         | $P_{\text{orb}}$ (d) | $P_s$ (s) | $L_{X,33}$ | $B_{12,\text{max}}$ | $B_{12,\text{max}}$ | References |
|----------------|----------------------|-----------|------------|---------------------|---------------------|------------|
| IGR J11215–5952| 165                  | 186.8     | $\sim 10$ | 3.5                 | 2.9                 | 1          |
| IGR J16465–4507| 30.3                 | $\sim 228$| $\sim 40$ | 8.9                 | 3.73                | 2          |
| AX J1841.0–0536| 4.74                 | $\sim 2$  | $2.2 \times 10^{-2}$ | $2.3 \times 10^{-2}$ | 3           |
| IGR J18483–0311| 18.55                | 21.05     | $\sim 10$ | 0.28                | 0.17                | 4          |

References. (1) Romano et al. 2009b; (2) Zurita Heras & Walter 2004; (3) Romano et al. 2009a; (4) Giunta et al. 2009.
in binaries are traditionally thought to be born as rapidly rotating (~10 ms) radio pulsars, spinning down by magnetic dipole radiation until the ram pressure of the ambient wind material from the companion star overcomes the pulsar’s radiation pressure at the gravitational radius. In the subsequent evolution the NS will rapidly spin-down by losing energy into the surrounding envelope material, until either $P_{\text{eq}}$ or $P_{\text{orb}}$ is reached, and a bright X-ray source emerges (Davies & Pringle 1981). Note that most of the evolution should be finished when the companion star is still unevolved. For a typical mass-loss rate of $10^{-8}$–$10^{-9}$ M$_{\odot}$ yr$^{-1}$ from a 30 M$_{\odot}$ main-sequence star and a wind velocity of $v_{\infty} \sim 10^3$ km s$^{-1}$, the accretion rate of the NS is $\sim 10^{15}$–$10^{16}$ g s$^{-1}$ if $P_{\text{orb}} \sim 10$–100 d. Since the spin-down time during the radio pulsar phase occupies the majority of the spin-down evolution (Davies & Pringle 1981), we can use it to estimate the total spin-down time:

$$\tau \simeq 8 \times 10^7 (B_{12}/0.1)^{-1} M_{10}^{-1/2} v_{8}^{-1} \text{ yr},$$

where $v_8 = v_{\infty}/10^8$ cm s$^{-1}$. This is at least one order of magnitude larger than the main-sequence lifetime ($\lesssim 5 \times 10^7$ yr) of the companion star, indicating that the current NSs should be in the pulsar phase with periods less than ~1 s, obviously in contrast with the observations of SFXTs. Hence, the traditional spin-down evolution mechanisms do not apply at least for some SFXTs.

The problem may be resolved in two ways. The first is that the wind of the companion star was not spherically expanding, but has had an asymmetric form, e.g., a disc-like wind with high density and low velocity as observed in Be stars. In this respect, it is interesting to see that IGR J11215–5952 is indeed located in the Be/X-ray binary region in the $P_{\text{orb}}$–$P$ diagram and shows periodic outbursts.

The alternative (and probably more general) possibility is that the NS was born rotating slowly ($P_i \lesssim 1$ s), so that it went directly into the propeller phase after its birth. Propeller spin-down to either $P_{\text{eq}}$ or $P_{\text{orb}}$ would take a time less than the main-sequence lifetime of the massive companion star (Li & van den Heuvel 1999, and references therein),

$$\tau \simeq 2.7 \times 10^7 (B_{12}/0.1)^{-1} M_{10}^{-3/4} P_i^{-3/4} \text{ yr},$$

where $P_i = P_i/1$ s.

In the latter case, these SFXTs will be distinct by relatively low fields and long initial spin periods from normal young NSs. These objects have been so-called “anti-magnetars” (young NSs born with a weak dipole field), originally discovered in the compact central objects (CCOs) in supernova remnants. For example, 1E 1207.4–5209, the peculiar CCO in the supernova remnant G296.5+10.0, has been proposed to be an anti-magnetar. Its spin period of 0.424 s (Zavlin et al. 2000) and the upper limit to its period derivative $\dot{P} < 2.5 \times 10^{-16}$ s$^{-1}$ (Gotthelf & Halpern 2007) yield a dipole magnetic field $B < 3.3 \times 10^{11}$ G. The characteristic age of the NS $\tau_{\tau} > 27$ Myr exceeds by three orders of magnitude the age of the supernova remnant, suggesting that 1E 1207.4–5209 was born with a spin period very similar to the current one. Evidence for similar low magnetic fields has been obtained for two other members of the CCO class, namely CXOU J185238.6+004020 at the centre of the Kes 79 SNR (Halpern et al. 2007) and RX J0822–4300 in Puppis A (Gotthelf & Halpern 2009).

We note that the above arguments still suffer the statistical problem because very few SFXTs have a magnetic field estimated. Indeed, SFXTs do exhibit diverse behaviours. For all of the most extreme SFXTs (e.g. IGRJ17544–2619, IGRJ08408–4503 and XTEJ1739–302), the spin periods have not yet been detected, and in a few cases very long spin periods have been suggested (up to 1000–2000 s; see Smith et al. 2006) and equations (6) and (7) suggest that the magnetic field strengths can be as high as a few $10^{13}$ G (see also Bozzo et al. 2008). For those SFXTs that host very slowly spinning NSs, there is no problem to spin-down to current periods within ~1 yr (Zhang, Li & Wang 2004). If confirmed, they indicate that SFXTs may belong to different classes of objects and their origins will be an interesting subject for future investigation.

**4 CONCLUSIONS**

We have derived possible constraints on the upper limit of magnetic field strengths of NSs in four SFXTs from recent observational results. Among them the only ‘real’ SFXT AX J1841.0–0536 may have a relatively low field ($\lesssim 10^{10}$ G) and a long initial spin period (~1 s), while the field strengths of the other three are considerably stronger. If AX J1841.0–0536 is not an extreme case, it suggests that the NSs in some SFXTs may represent another kind of anti-magnetars besides the CCOs discovered in supernova remnants and have interesting implications for the formation of young NSs born with relatively low fields and long spin periods. Future observations especially the detection of the cyclotron features in the X-ray spectra of SFXTs and monitoring their spin evolution to constrain the accretion torques will be crucial in unveiling the nature of the NSs in SFXTs.

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