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Feeding Neutron Stars in High-Mass X-ray Binaries

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Abstract. We suggest that the Be/X-ray binary SXP 1062 and the supergiant fast X-ray transient AX J1841.0−0536 belong to accreting magnetars and anti-magnetars, respectively.

Keywords. Stars: neutron, X-rays: binaries: SXP 1062, AX J1841.0−0536

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1. Introduction

Pulsars are strongly magnetized neutron stars (NSs) with typical field strengths $\sim 10^{11} - 10^{13}$ G. However, there are a small number of young, isolated NSs possess surface magnetic fields of either $\gtrsim 10^{14}$ G or $\lesssim 10^{10}$ G. They are called magnetars and anti-magnetars, respectively. Currently, such exotic objects have not been identified in accreting binaries. Here we show that the Be/X-ray binary SXP 1062 and the supergiant fast X-ray transient AX J1841.0−0536 may belong to accreting magnetars and anti-magnetars in high-mass X-ray binaries (HMXBs), respectively.

2. The magnetar candidate SXP 1062

SXP 1062 is a Be/X-ray binary discovered in the Small Magellanic Cloud (Haberl *et al.* 2000). With an X-ray luminosity $L_{\rm X} \simeq 6.3 \times 10^{35}\,{\rm erg\,s^{-1}}$ and a pulse period of $P \simeq 1062\,{\rm s}$, SXP 1062 was found to be located in the center of a shell-like nebula, which is considered to be a supernova remnant (SNR), aging only $\sim 10 - 40$ kyr (Haberl *et al.* 2012; Hénault-Brunet *et al.* 2012). Thus SXP 1062 provides the first example of an X-ray pulsar associated with a SNR. Haberl *et al.* (2012) showed that the NS in SXP 1062 has a very large average spin-down rate with the spin frequency derivative $\dot{\nu} \sim 2.6 \times 10^{-12}\,{\rm Hz\,s^{-1}}$ (or period derivative $\dot{P} \sim 100\,{\rm s\,yr^{-1}}$). If the NS has a normal magnetic field ($B \sim 10^{12} - 10^{13}$ G), it's hard to spin-down to a period $\sim 1000\,{\rm s}$ within a few 10^4 years.

The cyclotron features in the X-ray spectra provide the most direct and accurate way to measure the magnetic field strengths of accreting NSs. Unfortunately, they have not been detected in SXP 1062. Nevertheless, there are several other ways to estimate the NS magnetic field from its spin period and period derivative (Fu & Li 2012). In the following we take the NS mass $M = 1.4M_{\odot}$, radius $R = 10^6$ cm and the moment of inertia $I = 10^{45}$ gcm^2.

The young age of the SNR associated with the NS. requires that the lifetime of the ejector phase must end within a few 10^4 years. Assuming that the magnetic field has changed little during this phase, one can estimate the timescale of the ejector phase to be (Popov & Turolla 2012)

$$\tau_{\rm ej} \sim 1.5\,\dot{M}_{16}^{-1/2} v_{300}^{-1/2} B_{12}^{-1}\,{\rm Myr}, \tag{2.1}$$

where $\dot{M} = 10^{16}\dot{M}_{16}$ gs^{-1} is the mass capture rate, $v = 300 v_{300}$ kms^{-1} is the wind velocity, and $B = 10^{12}B_{12}$ G is the field strength. This value is about two orders of magnitude larger than the estimated age of SXP 1062, unless $B_{12} > 100$. This means that SXP 1062 must have possessed very strong magnetic field.

The extraordinary large spin-down rate of SXP 1062 can be used to put useful constraint on the magnetic field of the NS. The maximum spin-down torque exerted on a NS in either disc or spherical accretion is (Lipunov 1982)

$$2\pi I\dot{\nu} = -\kappa\frac{\mu^2}{R_{\rm co}^3}, \tag{2.2}$$

where μ is the magnetic moment, $R_{\rm co}$ the corotation radius, and $\kappa < 1$. To account for the spin-down rate measured in SXP 1062, the NS magnetic field has to be

$$B \simeq 3\times 10^{14}\kappa^{-1/2}(\dot{P}/100\,{\rm s\,yr}^{-1})^{1/2}\ {\rm G}. \tag{2.3}$$

Illarionov & Kompaneets (1990) argued that there could be outflows from the NS magnetosphere caused by heating of hard X-ray emission of the NS if the X-ray luminosity falls in the range of $\sim 2\times 10^{34}$ ergs^{-1} $-$ 3×10^{36} ergs^{-1}. Compton scattering heats the accreted matter anisotropically, and some of the heated matter with a low density can flow up and form outflows to take the angular momentum away. The corresponding spin-down torque is

$$2\pi I\dot{\nu} = -\kappa\chi\dot{M}_{\rm out}\nu R_{\rm m}. \tag{2.4}$$

Here $\dot{M}_{\rm out}$ is the mass outflow rate, $R_{\rm m}$ the magnetospheric radus and χ the solid angle of the outflow. This gives the magnetic field to be

$$B \simeq 3.6\times 10^{14}\left(\frac{\kappa\chi}{2\pi}\right)^{-7/8}\left(\frac{\dot{M}_{\rm out}}{10^{16}\ {\rm gs}^{-1}}\right)^{-3/8}\left(\frac{\dot{P}}{100\,{\rm s\,yr}^{-1}}\right)^{7/8}\left(\frac{P}{1062\,{\rm s}}\right)^{-7/8}\ {\rm G}. \tag{2.5}$$

Ikhsanov & Finger (2012) suggested that if the accreting material is magnetized, the magnetic pressure in the accretion flow increases more rapidly than its ram pressure, and under certain conditions the magnetospheric radius is considerably smaller than the traditional magnetospheric radius. The spin-down torque applied to the NS is found to be

$$2\pi I\dot{\nu} = -\frac{\kappa_m\mu^2}{(R_{\rm co}R_{\rm m})^{3/2}}, \tag{2.6}$$

where κ_m is a dimensionless efficiency parameter for the magnetic viscosity coefficient, and $0 < \kappa_m < 1$. In the case of SXP 1062, it results in the estimate of the magnetic field to be

$$B \simeq 2\times 10^{14}\kappa_{0.1}^{-13/17}\dot{M}_{16}^{-6/17}T_6^{-3/17}\left(\frac{\dot{P}}{100\,{\rm s\,yr}^{-1}}\right)^{13/17}\left(\frac{P}{1062\,{\rm s}}\right)^{-13/17}\ {\rm G}, \tag{2.7}$$

where $\kappa_{0.1} = \kappa_m/0.1$ and $T = 10^6 T_6$ is the plasma temperature at the magnetospheric boundary.

3. The anti-magnetar candidate AX J1841−0536

A new type of HMXBs was discovered by INTEGRAL, called supergiant fast X-ray transients (SFXTs; see Sidoli 2011, for a recent review). These sources are characterized by X-ray outbursts composed of short bright flares up to peak luminosities of $\sim 10^{36}-10^{37}$

ergs^{-1}, with the duration of a few hours for each single flare. In quiescence, the luminosity is as low as 10^{32} ergs^{-1}. X-ray pulsations have been detected in a few sources, leading to the firm identification of the compact object as an NS. Recent observations revealed that SFXTs spend most of their life still accreting matter even outside bright flaring activity rather in quiescence, emitting at an intermediate level luminosity $\sim 10^{33} - 10^{34}$ ergs^{-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 always only a few hundred meters, clearly associated with the polar caps of the NSs.

If steady accretion occurs during the intermediate state, one possible implication is that the plasma at the base of the NS magnetosphere 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 & Lamb 1977). 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). Thus we first take the simplest assumption that direct accretion occurs with the help of KHI if the magnetospheric radius of the NS is smaller than the corotation radius. Equivalently the NS has a spin period longer than the equilibrium period,

$$P \geqslant P_{\rm eq} \simeq 165.5 B_{12}^{6/7} \dot{M}_{13}^{-3/7}\ {\rm s}, \tag{3.1}$$

where $\dot{M}_{13} = \dot{M}/10^{13}$ gs^{-1}. This condition sets the maximum of the magnetic field strength of the NS as,

$$B_{12,max} \simeq 0.085 (P/20\,{\rm s})^{7/6} \dot{M}_{13}^{1/2}. \tag{3.2}$$

The above derivations are based on the assumption that there is direct accretion during the intermediate state. However, even if the magnetospheric boundary is stable against RTI or KHI, in the subsonic propeller phase, 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 (2001) and Bozzo *et al.* (2008). If the intermediate level X-ray luminosities are really produced by field penetration, then we can safely derive that, during outbursts direct accretion must take place, or the NS spin period must be longer than the corresponding break period. Taking $\dot{M} \simeq 10^{16}$ gs^{-1}, we can estimate the maximum of the field strength

$$B_{12,max} \simeq 0.15 (P/20\,{\rm s})^{21/16}. \tag{3.3}$$

Taking $P = 4.74$ s and $L_{\rm X} \simeq 2 \times 10^{33}$ ergs^{-1} for AX J1841.0−0536, its magnetic field can be estimated to be $\sim 10^{10}$ G (Li & Zhang 2011).

If AX J1841.0−0536 is a low-field NS, it is interesting to see how they have evolved to the current spin periods. 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,

$$\tau \simeq 8 \times 10^{8} (B_{12}/0.01)^{-1} \dot{M}_{16}^{-1/2} v_8^{-1}\ {\rm yr}, \tag{3.4}$$

where $v_8 = v/10^8$ cms^{-1}. This is at least one order of magnitude larger than the main-sequence lifetime (a few 10^6 yr) of the companion star.

One possible solution is that the NS was born rotating slowly ($P_{\rm s} \lesssim 1$ s), so that it went directly into the propeller phase after its birth. In this case, AX J1841.0−0536 will be distinct by relatively low fields and long initial spin periods from normal young NSs, similar to the so called “anti-magnetars” (young NSs born with a weak dipole field), originally discovered in the compact central objects (CCOs) in supernova remnants.

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