Accreting magnetars: linking ultraluminous X-ray pulsars and the slow pulsation X-ray pulsars

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ABSTRACT

Possible manifestations of accreting magnetars are discussed. It is shown that the four ultra-luminous X-ray pulsars can be understood in the accreting low magnetic field magnetar scenario. The NGC300 ULX1 pulsar may have a higher dipole magnetic field than other sources. This may explain why its has the longest rotational period and largest spin-up rate in the four ULX pulsars. General constraint on their mass accretion rate confirmed their super-Eddington nature. Lower limits on their beaming factor are obtained. They do not seem to have strong beaming. The duty cycle of the ULX burst state can also be constrained by their timing observations. It is proposed that the slowest pulsation X-ray pulsar AX J1910.7+0917 may be an accreting magnetar with a low mass accretion rate. ULX pulsars, slow pulsation X-ray pulsars may all be accreting magnetars with different accretion rates. These special accreting neutron stars may be linked together in the accreting magnetar scenario. Seven possible signatures of an accreting magnetar are summarized.

Key words: accretion – stars: magnetar – stars: neutron – pulsars: general – pulsars: individual (AX J1910.7+0917).

1 INTRODUCTION

Magnetars form a special kind of pulsars. They may have magnetic field as high as $10^{15}$ G (Duncan & Thompson 1992; Kaspi & Beloborodov 2017). Strong magnetic field powers magnetar’s persistent emissions and bursts. Observationally, some magnetars with low dipole magnetic field were found (Rea et al. 2010; Zhou et al. 2014). Their dipole magnetic field can be several times $10^{12}$ G. These low magnetic field magnetars may be old magnetars (Turolla et al. 2011; Tong & Xu 2012). From the early time of magnetar researches, one open question is: where are accreting magnetars (Woods & Thompson 2006)? It is expected that there are some accreting magnetars in binary systems. The problem is: how to find the signature of an accreting magnetar from the zoo of accreting neutron stars?

Previously, it is speculated that magnetar-like bursts and a hard X-ray tail above 100 keV are the two observational signatures of accreting magnetars (Tong & Wang 2014). Ultraluminous X-ray (ULX) pulsars are accreting neutron star with X-ray luminosity as high as $10^{40}$ erg s$^{-1}$ or higher (Bachetti et al. 2014). It is pointed out that ULX pulsars may be another manifestation of accreting magnetars (Eksi et al. 2015; Tong 2015; Dall’Osso et al. 2015). The ultra-strong magnetic field (which can be as high as $10^{15}$ G) may be responsible for the super-Eddington luminosity. However, different authors give different estimations of the neutron star’s dipole magnetic field. Since old magnetars are more likely to be low magnetic field magnetars, it is proposed that the ULX pulsars may be accreting low magnetic field magnetars (Tong 2015). Later discovery of more ULX pulsars are consistent with the accreting low magnetic field magnetar scenario (Fürst et al. 2016; Israel et al. 2017a,b; Carpano et al. 2018).

If ULX pulsars are accreting magnetars with a very high mass accretion rate, then some accreting magnetars with relative low mass accretion rates are also expected. Accretion systems are often in a spin equilibrium state (Bhattacharya & van den Heuvel 1991; Ho et al. 2014). The equilibrium period of accreting neutron stars depends on the stellar magnetic field and the mass accretion rate: $P_{eq} \propto B^{6/7} M^{-3/7}$.

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There are also models using normal neutron stars for ULX pulsars (e.g., King et al. 2017; Chrostodoulou et al. 2017, 2018).
The rotational periods of ULX pulsars are about several seconds. Then, accreting magnetars with low mass accretion rates may have long rotational periods. In this respect, the slowest pulsation X-ray pulsar AX J1910+0917 with a rotational period of $3.6 \times 10^3$ s may also be an accreting magnetar candidate (Sidoli et al. 2017). Other slow pulsation X-ray pulsars with rotational periods about $10^3$ s or longer are also proposed to be accreting magnetar candidates (Wang 2009, 2011; Reig et al. 2012; Yang et al. 2017). Therefore, a variety of accreting neutron stars may be linked together in the accreting magnetar scenario.

Detailed calculation for the four ULX pulsars in the accreting low magnetic field magnetar model is presented in section 2. The merit of understanding the slowest X-ray pulsar in the magnetar scenario is discussed in section 3. Discussions are given in section 4.

2 ULX PULSARS AS ACCRETING LOW MAGNETIC FIELD MAGNETARS

2.1 Three aspects of ULX pulsar observations

From the first discovery of Bachetti et al. (2014), four ULX pulsars are identified up to now (Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017a,b; Carpano et al. 2018). From these four sources, more can be learned about ULX pulsars.

(i) Pulse profile. All four sources exhibit near sinusoidal pulse profiles with broad pulse features. This means that ULX pulsars are not likely to have a strong beaming. At the same time, a near sinusoidal profile requires that ULX pulsars should have a moderate degree of beaming. A typical beaming factor of $b = 0.2$ may be chosen (Feng & Soria 2011). For a given source, its true X-ray luminosity is related to its isotropic X-ray luminosity as

$$L_x = b L_{x,\text{iso}} = b L_{x,\text{iso,40}} \times 10^{39} \text{ erg s}^{-1},$$

(1)

where $L_{x,\text{iso,40}}$ is the isotropic X-ray luminosity in units of $10^{39}$ erg s$^{-1}$. The mass accretion rate is related to the true X-ray luminosity as

$$L_x = \eta M c^2,$$

(2)

where $\eta$ is the energy conversion efficiency for accretion onto the neutron star. Typical values of $\eta = 0.1$ can be used (Frank et al. 2002).

(ii) Super-Eddington luminosity. The isotropic X-ray luminosity of ULX pulsars can be as high as $10^{41}$ erg s$^{-1}$ (Israel et al. 2017b). With a moderate beaming factor, the neutron star’s true X-ray luminosity can be 100 times the traditional Eddington luminosity. This confirms the super-Eddington nature of ULX pulsars. In the accreting magnetar scenario, a magnetic field strength $\geq 10^{14}$ G will result in a critical luminosity about $10^{41}$ erg s$^{-1}$ (Paczynski 1992; Mushotzky et al. 2015). Therefore, the super-Eddington luminosity of ULX pulsars can be safely understood in the accreting magnetar scenario.

(iii) Rotational behavior. All the four ULX pulsars have a variable luminosity. The X-ray luminosity in the high state can be one hundred times higher than the X-ray luminosity in the low state. When assuming accretion equilibrium of the neutron star, there may be ambiguities in determining which luminosity corresponds to the equilibrium state.

Similar ambiguities also exist when assuming transition between the accretion phase and the propeller phase due to the sparse of observations (Tsygankov et al. 2016; Israel et al. 2017a,b). Both of the above two assumptions will result in a magnetospheric radius equal to the corotation radius, which can be used to determine the dipole magnetic field of the central neutron star. Another way is to study the accretion torque and compare it with the the spin-up behavior. In this way, the dipole magnetic field can also be determined. Whether the neutron star is in accretion equilibrium can be determined thereafter.

2.2 Calculations of the dipole magnetic field

For M82 X-2, its pulsation period is $P = 1.37$ s, typical period derivative $\dot{P} = -2 \times 10^{-10}$ s$^{-1}$, typical isotropic X-ray luminosity when the pulsation is detected $L_{x,\text{iso}} \approx 10^{39}$ erg s$^{-1}$ (Bachetti et al. 2014). Following the above discussions, its true X-ray luminosity is

$$L_x = 2 \times 10^{39} \left( \frac{b}{0.2} \right) L_{x,\text{iso,40}} \text{ erg s}^{-1}.$$

(3)

For M82 X-2, its mass accretion rate is

$$\dot{M} = 2.2 \times 10^{19} \left( \frac{b}{0.2} \right) \left( \frac{\eta}{0.1} \right)^{-1} L_{x,\text{iso,40}} \text{ g s}^{-1}.$$

(4)

During the accretion phase, the spin-up torque is dominated by the matter inflow (Ghosh & Lamb 1979; Lai 2014). This corresponds to the slow-rotator scenario for accreting neutron stars (Ghosh & Lamb 1979). During the outburst, the luminosity of ULX pulsars can vary by a factor 10 (Israel et al. 2017a,b). When the luminosity is 10 times lower than the peak luminosity, the ULX pulsar is still in the accretion phase. At the peak luminosity, the corresponding Alfvén radius, eq. (4), is smaller. Therefore, a slow rotator assumption may be reasonable. The spin-up of the neutron star is governed by

$$I \ddot{\Omega} = -2\pi I \frac{\dot{P}}{P^2} = M \sqrt{GM\dot{M}} R_A,$$

(5)

where $I$ and $M$ is the neutron star moment of inertia and mass, respectively, $R_A$ is the Alfvén radius. The Alfvén radius is determined by the dipole magnetic moment and mass accretion rate (Shapiro & Teukolsky 1983; Lai 2014)

$$R_A = 3.2 \times 10^8 \mu_{30}^{4/7} R_1^{-1/7} M_7^{2/7} \text{ cm},$$

(6)

where $\mu = 1/2B_g R^3$ is the magnetic dipole moment of the neutron star, $\mu_{30}$ is the dipole moment in units of $10^{30}$ G cm$^3$, $M_7$ is the neutron mass in units of solar masses, $M_7$ is the mass accretion rate in units of $10^{-7}$ g s$^{-1}$, $B_g$ is the polar dipole magnetic field$^2$, and $R$ is the neutron star radius. From equation (5), the dipole magnetic field of M82 X-2 can be determined

$^2$ The magnetosphere radius is assumed to be equal to the Alfvén radius. A commonly employed factor of 0.5 is not included, because the accretion disk for ULX pulsars may become thick and the geometry may be similar to the spherical case (King et al. 2017; Walton et al. 2018a).

$^3$ The dipole magnetic field at the equator is two times smaller than the polar magnetic field (Shapiro & Teukolsky 1983).
\[ B_p = 2.1 \times 10^{10} \left( \frac{b}{0.2} \right)^{-3} \left( \frac{\eta}{0.1} \right)^{3} L_{x,iso,40}^{-3} \text{G.} \]  

(7)

Typical values of \( M = 1.4 M_\odot, R = 10 \text{ km, and } I = 10^{-9} \text{g cm}^2 \) are adopted during the calculations.

The equilibrium period is reached when the magnetic field of M82 X-2 can be as high as \( 10^{14} \text{ G} \). For Swift J0243.6+6124, which is a candidate ULX pulsar in the Swift catalogue, its pulsation period is about 0.02 s, long term spin-up rate \( P = -5 \times 10^{-13} \text{ s}^{-1} \), typical isotropic X-ray luminosity when pulsation is detected \( L_{x,iso} = 10^{39} \text{ erg s}^{-1} \) (Fürrst et al. 2016; Israel et al. 2017). Similar to the above calculations, the dipole magnetic field of M82 X-2 is about: \( B_p = 6 \times 10^{12} \left( \frac{b}{0.2} \right)^{-3} \left( \frac{\eta}{0.1} \right)^{3} L_{x,iso,41}^{-3} \text{G} \), where \( L_{x,iso,41} \) is the star’s isotropic X-ray luminosity in units of \( 10^{41} \text{ erg s}^{-1} \) and is the parameter \( L_{x,iso,41} \) is the parameter \( (PL_x^{2/7})^2 \) is also plotted, which shows a general trend of a positive correlation.

Possible correlations of this kind have been found in normal accreting neutron stars (Sugizaki et al. 2017). Future more observations may help to test such correlations in ULX pulsars.

2.4 General constraint on the mass accretion rate, beaming factor and dipole magnetic field

In the above calculations, a specific beaming factor is assumed. Some general constraints on the mass accretion rate, beaming factor and dipole magnetic field can be obtained for ULX pulsars. The following calculations are motivated by Chen (2017)’s calculation for M82 X-2.

During the outburst state, ULX pulsars are spinning up due to accretion. The spin-up torque should be dominated by the matter torque, equation \( \Box \). For accretion to occur, the Alfvén radius should be smaller than the corotation radius.

\[ R_A \leq R_{co} \equiv \left( \frac{GM}{4\pi^2} \right)^{1/3} P^{2/3}. \]  

(11)

By combining equation \( \Box \) and (11), a lower limit on the mass accretion rate can be obtained.

\[ \dot{M} \geq \dot{M}_{\text{min}} = 3.6 \times 10^{18} \left( \frac{P}{10^{13} \text{s}} \right)^{-7/3} \text{ g s}^{-1}, \]  

(12)

\( B_p \) is the dipole magnetic field of M82 X-2 and can be as high as \( 10^{12} \text{ G} \). For example, for an energy conversion efficiency of \( \eta = 0.3, \) which corresponds to accretion onto a neutron star with mass \( 2M_\odot \) and radius \( 10 \text{ km} \), the dipole magnetic field of M82 X-2 is about \( 0.6 \times 10^{12} \text{ G} \). And a beaming factor two times smaller (about 0.1) will enhance the result by a factor of eight.

\( \Box \) For Swift J0243.6+6124, which is a candidate ULX pulsar in the Swift catalogue, similar calculations showed that it has dipole magnetic field of \( 2.7 \times 10^{13} \text{ G} \). The commonly reported magnetic field at the equator is two time smaller, about \( 1.3 \times 10^{13} \text{ G} \). It is consistent with the result of Doroshenko et al. (2018) and justifies our slow rotator assumption.

For NGC300 ULX1 pulsar, it pulsation period is \( P = 31.6 \text{ s} \), period derivative \( P' = -5.56 \times 10^{-7} \text{s}^{-1} \), and typical X-ray luminosity \( L_{x,iso} = 4.7 \times 10^{39} \text{ erg s}^{-1} \) (Carpano et al. 2018). Similar calculations showed that the dipole magnetic field of NGC300 ULX1 pulsar is about: \( B_p = 6.7 \times 10^{13} \left( \frac{b}{0.2} \right)^{-3} \left( \frac{\eta}{0.1} \right)^{3} \left( \frac{L_{x,iso}}{4.7 \times 10^{39} \text{ erg s}^{-1}} \right)^{-3} \text{G} \). It dipole field is the highest among the four ULX pulsars. This may explain why it has the longest pulsation period and largest spin-up rate.
The diagrams of the observed three parameters in ULX pulsars: $P$, $P$ and $L_x$. In the top panel, we also plot the diagram of $-\dot{P}$ versus $(PL_x^{3/7})^2$. Where typical values of period and period-derivative are inserted. Using the timing observations of the four ULX pulsars, their minimum mass accretion rates are: $3.4 \times 10^{18}$ g s$^{-1}$ (for M82 X-2), $9.4 \times 10^{18}$ g s$^{-1}$ (for NGC7793 P13), $1.3 \times 10^{19}$ g s$^{-1}$ (for NGC5907 ULX pulsar), and $6.3 \times 10^{18}$ g s$^{-1}$ (for NGC300 ULX1). This confirms their super-Eddington nature.

Using the lower limit for the mass accretion rate, a lower limit on the beaming factor can be obtained: $L_x = bL_{x,iso} = \eta \dot{M} c^2 \geq \eta \dot{M}_{\text{min}} c^2$. The lower limit on the beaming factor is

$$b \geq b_{\text{min}} = \frac{\eta \dot{M}_{\text{min}} c^2}{L_{x,iso}}$$

For the four ULX pulsars, the lower limits on their beaming factors are: $0.03(\dot{\eta}/0.1)L_{x,iso,40}^{-1}$ (for M82 X-2), $0.08(\dot{\eta}/0.1)L_{x,iso,40}^{-1}$ (for NGC7793 P13), $0.12(\dot{\eta}/0.1)L_{x,iso,41}^{-1}$ (for NGC5907 ULX pulsar), and $0.12(\dot{\eta}/0.1)L_{x,iso}/4.7 \times 10^{20}$ erg s$^{-1}$ (for NGC300 ULX1). In the previous section, a beaming factor of $b = 0.2$ is assumed. It is consistent with the lower limits obtained here. In some calculations, a strong beaming factor is assumed. The lower limits here are not in strong support for this scenario. Furthermore, considering that the beaming factor should be smaller than one $b \leq 1$, an upper limit on the mass accretion rate can be obtained. From $\eta \dot{M} c^2 = bL_{x,iso} \leq L_{x,iso}$, then

$$\dot{M} \leq \dot{M}_{\text{max}} = \frac{L_{x,iso}}{\eta c^2} = 10^{20} \left( \frac{\eta}{0.1} \right)^{-1} L_{x,iso,40} \text{g s}^{-1}.$$  \hspace{1cm} (14)

For M82 X-2, NGC7793 P13, and NGC300 ULX1, the upper limit on their mass accretion is about $10^{20}$ g s$^{-1}$. For NGC5907 ULX pulsar, its isotropic X-ray luminosity can be as high as $10^{41}$ erg s$^{-1}$. The upper limit on its mass accretion is about $10^{21}$ g s$^{-1}$.

From equation (11), an upper limit on the dipole magnetic field as a function of mass accretion rate can be obtained

$$B_0 \leq B_{p,\text{max}} = 2.2 \times 10^{12} \dot{M}_{18}^{1/2} P^{7/6} \text{G},$$  \hspace{1cm} (15)

where $\dot{M}_{18}$ is the mass accretion rate in units of $10^{18}$ g s$^{-1}$. Since pulsation can be detected from the ULX pulsars, their Alfvén radius should be larger than the neutron star radius $R_\star \geq R$. This means that the neutron star dipole magnetic field can not be arbitrarily small. This places a lower limit on the neutron star dipole magnetic field (as a function of mass accretion rate)

$$B_0 \geq B_{p,\text{min}} = 2.8 \times 10^8 \dot{M}_{18}^{1/2} \text{G}.$$  \hspace{1cm} (16)

This idea is similar to that of accreting normal neutron stars (Bildsten et al. 1997; Zhang & Kojima 2006). Accreting neutron stars in high mass X-ray binaries are often observed as X-ray pulsars. While, the pulsation of accreting neutron stars in low mass X-ray binaries are often not detected. This may because neutron stars in low mass X-ray binaries have a lower dipole magnetic field. This also means that if some accreting magnetars have a low dipole magnetic field, then they may not been observed as pulsating sources. Finding pulsations is only one way to confirm the neutron star nature of ULX sources.

For every ULX pulsar, they have both lower limit and
upper limit on the mass accretion rate. Therefore, the upper/lower limits of their dipole magnetic field can be plotted as a function of their mass accretion rate. From equation (5), the neutron star dipole magnetic field can be found as a function of the true mass accretion rate

$$B_p = 2 \times 10^{14} M_{18}^3 \left( \frac{P}{10^{-10}} \right)^{7/2} \left( \frac{P}{1 s} \right)^{-7} \mathrm{G}. \tag{17}$$

Considering the super-Eddington nature of ULX pulsars, their mass accretion rate can be very high $\dot{M} \gg 10^{18} \mathrm{g \, s^{-1}}$. This will result in $B_p \ll 2 \times 10^{14} \mathrm{G}$. This is in general consistent with the accreting low magnetic field magnetar scenario.

Figure 2 shows the dipole magnetic field vs. the mass accretion rate of ULX pulsars. In Figure 2, the region between the two dot-dashed lines and two dashed lines is the allowed range of dipole magnetic field and mass accretion rate. In this region, the solid line is a possible solution, equation (17). While, in the calculation of section 2.2, a specific beaming factor and accretion efficiency is used. This corresponds to one point on the solid line in figure 2.

2.5 Duty cycle of the ULX state and accretion equilibrium

Observationally, the ULX pulsars switch between the high luminosity state and the low luminosity state. This may due to the transition of the neutron star between the accretion phase and the propeller phase (Tong 2015; Dall’Osso et al. 2015; Tsygankov et al. 2016). X-ray luminosity observations may tell us some information of the duty cycle of the ULX state (high luminosity state). A finite duty cycle of the ULX state will also affect the timing behavior of the neutron star in two aspects.

(i) The neutron star will spin up during the ULX state, and spin down during the low luminosity state. On the long term run, the neutron star may approach an equilibrium period. This will be more physical compared with defining a rough long term averaged mass accretion rate, equation (5).

(ii) The neutron star’s measured spin-up torque will be larger during the ULX state than its long term averaged value. This has already been found in observations (Israel et al. 2017b).

A unified torque for the accretion phase and the propeller phase may be employed (Menu et al. 1999; Tong et al. 2016)

$$N \propto M R_A^2 \Omega_K(R_A) \left( 1 - \frac{\Omega}{\Omega_K(R_A)} \right), \tag{18}$$

where $\Omega_K(R_A)$ is the Keplerian angular velocity at the Alfvén radius. Denote the the accretion rate during the ULX state (high state) as $M_h$, its duty cycle as $D_p$. Denote the mass accretion rate during the low state as $M_l$, and its duty cycle will be $1 - D_p$. The rotational evolution of the neutron star is governed by $N = H \dot{\Omega}$. Accretion equilibrium means that:

$$\int N dt = I \Delta \Omega = 0,$$

therefore

$$M R_A^2 \Omega_K(R_A)|_{M=M_h} D_p$$

$$- \dot{M} R_A^2 \Omega_K(R_A) \frac{\Omega}{\Omega_K(R_A)}|_{M=M_l} (1 - D_p) = 0. \tag{19}$$
Solving for the duty cycle

\[
1 - \frac{D_p}{D_{\rho}} = \frac{\dot{M} R_\text{A}^2 \Omega_K (R_A)_{\dot{M}=\dot{M}_h}}{M R_\text{A}^2 \Omega_{\dot{M}=\dot{M}_l}}.
\] (20)

Using that the Alfvén radius is proportional to \(\dot{M}^{-2/3}\) (equation 18), then

\[
1 - \frac{D_p}{D_{\rho}} = \left(\frac{\dot{M}_h}{\dot{M}_l}\right)^{3/7} \frac{\Omega_K (R_A)_{\dot{M}=\dot{M}_h}}{\Omega} \quad (21)
\]

\[
= \frac{\dot{M}_h}{\dot{M}_l} \frac{1}{\omega_s}, \quad (22)
\]

where \(\omega_s = \Omega/\Omega_K (R_A)_{\dot{M}=\dot{M}_h}\) is the fastness parameter during the ULX state. In the accretion state, the fastness parameter is smaller than one: \(\omega_s < 1\). Then

\[
1 - \frac{D_p}{D_{\rho}} > \left(\frac{\dot{M}_h}{\dot{M}_l}\right)^{3/7}. \quad (23)
\]

Further simplification of the above equation shows that

\[
D_p < \left(\frac{\dot{M}_l}{\dot{M}_h}\right)^{3/7}. \quad (24)
\]

For typical values of \(\dot{M}_l \sim 10^{38} \text{ g s}^{-1}\) and \(\dot{M}_h \sim 10^{39} \text{ g s}^{-1}\), the upper limit on the duty cycle of the ULX state (especially for the peak luminosity) is \(D_p < 14\%\). This limit on the duty cycle of the ULX state is roughly consistent with the X-ray observations (Tsyganov et al. 2016; Fürst et al. 2016; Israel et al. 2017a,b).

3 ACCRETING MAGNETAR SCENARIO FOR SLOW PULSATION X-RAY PULSARS

The X-ray source AX J1910.7+0917 has pulsation period of 36.2 ks \(\sim 10\) h (Sidoli et al. 2017). Its X-ray luminosity ranges from \(1.7 \times 10^{34} \text{ erg s}^{-1}\) to \(10^{36} \text{ erg s}^{-1}\). It may be the slowest pulsation X-ray pulsar at present. The nature of AX J1910.7+0917 may be a wind accreting neutron star with normal magnetic field about \(10^{12} \text{ G}\) (Sidoli et al. 2017 and references therein). According to the equilibrium period of disk accretion, equation 18, if AX J1910.7+0917 has a dipole magnetic field of \(4 \times 10^{15} \text{ G}\) (corresponds to \(B_{\text{eq}} = 2 \times 10^3\)) and accretion rate of \(\dot{M}_{\text{eq}} \sim 10^{-3}\), then its pulsation period can also be understood in the accreting magnetar scenario. It has a very long pulsation period because its magnetar strength dipole magnetic field and a low accretion rate. The variation of its X-ray luminosity may due to variation of the mass accretion rate or transition between accretion phase and propeller phase. The later possibility may be similar to the variation of X-ray luminosity of ULX pulsars.

Observations of other slow pulsation X-ray pulsars may give some indirect support for the accreting magnetar nature of AX J1910.7+0917.

- The long period neutron star 4U 0114+65 may be an accreting magnetar candidate (Sanjurjo-Ferrrin et al. 2017). Possible signature of a transient disk was also found (Hu et al. 2017).
- The central neutron star inside the supernova remnant RCW 103 may have a rotational period about 6.7 hours (De Luca et al. 2006). Magnetar-like activities were found in this source, confirming its magnetar nature (Rea et al. 2016; D’Ai et al. 2016). The physical reason for its long rotational period may be accretion from a fallback disk (Tong et al. 2016). Therefore, the long period neutron star inside RCW 103 is a magnetar accreting from a fallback disk.

The spin-down torque due to a disk is very efficient. If AX J1910.7+0917 has an initial rotational period similar to that of isolated magnetars (about 10 s) at the beginning of accretion, with dipole magnetic field of \(4 \times 10^{15} \text{ G}\), and mass accretion rate \(10^{14} \text{ g s}^{-1}\), then it can evolve to a rotational period about \(\sim 30\) ks is a very short time. Similar to the case of 4U 0114+65, the possible disk in AX J1910.7+0917 may be a transient accretion disk (i.e., the disk has a duty cycle smaller than one). Since the disk torque is very efficient, the transient disk may still dominate the rotational behavior of the central neutron star.

There are several merits of understanding the slowest X-ray pulsar AX J1910.7+0917 in the accreting magnetar scenario.

(i) If ULX pulsars are accreting magnetars with mass accretion rate about \(10^{36} \text{ g s}^{-1}\), then there can also be accreting magnetars with a lower mass accretion rate. The slowest X-ray pulsar with low luminosity and long period may correspond to this case.

(ii) The prediction for AX J1910.7+0917 is very clear if it is an accreting magnetar. With a magnetic field about \(10^{15} \text{ G}\), and a low mass accretion rate \(\dot{M} \sim 10^{34} \text{ g s}^{-1}\), inside the Galaxy, magnetar-like activities may also been observed in this source.

(iii) Different kinds of special accreting neutron stars may be linked together in the accreting magnetar scenario. (a) ULX pulsars may be accreting magnetars with high mass accretion rates. (b) The slow pulsation X-ray pulsars may be accreting magnetars with low mass accretion rates, including AX J1910.7+0917, 4U 0114+65 (Sanjurjo-Ferrrin et al. 2017), 4U 2206+54 (Reig et al. 2012) etc. Some supergiant fast X-ray transients (SFXTs, e.g. sources which can have very low X-ray luminosities, Walter et al. 2015) may be accreting magnetars transit between the accreting phase and the propeller phase (Bozzo et al. 2008). (c) Accreting magnetars with intermediate mass accretion rates \((10^{17} - 10^{18} \text{ g s}^{-1})\), and relative long spin period (\(\sim 1000\) s) may correspond to slow pulsation X-ray pulsars in the Small Magellanic Cloud (Klus et al. 2014; Ho et al. 2014). In Figure 3, we collected the spin period and orbital period of the known ULX pulsars, SFXT pulsars and slow pulsation pulsars in the Galaxy and the Small Magellanic Cloud.

ULX pulsars may have a very high mass accretion rate. The accreted matter may result in a decay of the magnetar’s magnetic field (Pan et al. 2016). It is similar to the accretion induced magnetic field decay in low mass X-ray binaries (Shibazaki et al. 1989; Zhang & Kojima 2006). This may explain why ULX pulsars tend to be accreting low magnetic field magnetars (besides possible magnetic field decay, Israel et al. 2018).
Other accreting magnetar candidates do not have such high mass accretion rate, the magnetic field decay there may not be very significant. This may be the first difference between ULX pulsars and other accreting magnetar candidates. Wind accretion may have difficulties in explain the very high X-ray luminosity of ULX pulsars. Therefore, the second difference is that ULX pulsars accretes via Roche lobe overflow (Bachetti et al. 2014), while slow pulsation X-ray pulsars are wind accreting systems. There are also links between ULX pulsars and slow pulsation X-ray pulsars. The possible transient disks in wind accreting neutron stars (Hu et al. 2017 and references therein) help to link these two kinds of accreting magnetar candidates. In Figure 3, it is suggested that longer orbital period may result in a longer rotational period of the neutron star for these accreting magnetar candidates. In the future, more observations are requested to discover more candidates, which could help us to understand the possible physical link between different classes of accreting magnetars.

Previously the two outstanding slow pulsation X-ray pulsars are 4U 0114+65 (or 2S 0114+65) and 4U 2206+54. The period derivative of AX J1910.7+0917 has not been determined at present (Sidoli et al. 2017). Adopting the typical value of 4U 2206+54 and 4U 0114+65, an absolute value of period derivative can be estimated to be ~ 10^{-6} s^{-1} (either spin-up or spin-down). The rotational period of AX J1910.7+0917 is determined to be 36200 ± 110 s at the year of 2011 (Sidoli et al. 2017). In about 30 years thereafter, the rotational period of AX J1910.7+0917 will change by an amount of ~ 1000 s. Timing observations of this source in the not very far future can test this possibility.

4 DISCUSSIONS

Accreting magnetars may have different mass accretion rate and different manifestations. However, confirming the central neutron star’s magnetar nature is not easy, since a lack of direct measurement of the neutron star’s magnetic field (Revnivtsev & Mereghetti 2015). There are many possible signatures of an accreting magnetar. A summary is listed in below.

(i) Magnetar-like outbursts. Similar things have already happened in confirming the magnetar nature of the RCW 103 central neutron star (Rea et al. 2016; D’Ai et al. 2016). However, it is not known at present whether and to what degree accretion will affect the magnetic activities of the central magnetar. At least in the case of low mass accretion rate, magnetic activities may still be present. Therefore, the slowest X-ray pulsar AX J1910.7+0917, and other long period X-ray pulsars may show some magnetar-like activities in the future.

(ii) A hard X-ray tail. Isolated magnetars tend to have a high X-ray tail above 100 keV compared with accreting normal neutron stars (Mereghetti et al. 2015). The possible signature of a hard X-ray tail in 4U 2206+54 and 4U 0114+65 may also hint a magnetar nature of the central neutron star (Reig et al. 2012; Wang 2011, 2013). This hard X-ray tail may be of magnetic origin (like isolated magnetars) or due to interaction of the soft X-ray photons with the accretion flow in strong magnetic field.

(iii) ULX pulsars. As in the case of magnetar giant flares (Paczynski 1992), a highly super-Eddington luminosity may be due to the presence of a magnetar strength magnetic field. The magnetic field concerned is the total magnetic field. While, the magnetic field appeared in torque studies is mainly the large scale dipole field.

(iv) Cyclotron line observations (if the final magnetic field is in the magnetar range). However, whether the line is due to electron or proton origin may be uncertain (Brightman et al. 2018; Walton et al. 2018b). The conclusion will be very different when assuming different origins.

(v) Switch between the accretion phase and propeller phase (If the final magnetic field is in the magnetar range). By figuring a specific luminosity corresponding to the transition, the magnetic field can be determined (Tsygankov et al. 2016).

(vi) ULX sources with pulsar-like spectra. Some sources may have small pulsed fraction due to interaction between the neutron star’s dipole magnetic field and the accretion flow. Pulsar-like spectra may indicate a neutron star at the center (Pintore et al. 2017; Walton et al. 2018a).
Slow pulsation X-ray pulsars. A slow pulsation combined with a low X-ray luminosity may indicate an accreting magnetar with low mass accretion rate. The slowest pulsation X-ray pulsar AX J1910.7+0917, besides other slow pulsation X-ray pulsars, may be such candidates.

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REFERENCES

Bachetti M., Harrison F. A., Walton W. J., et al., 2014, Nature, 514, 202
Bhattacharya D., van den Heuvel E. P. J., 1991, Physics Reports, 203, 1
Bildsten L., Chakrabarty D., Chiu J., et al., 1997, ApJS, 113, 367
Bozzo E., Falanga M., Stella L., 2008, ApJ, 683, 1031
Brightman M., Harrison F. A., Fürst F., et al., 2018, Nature Astronomy, 2, 312
Carpano S., Haberl F., Maitra C., et al., 2018, MNRAS, 476, L45
Chen W. C., 2017, MNRAS, 465, L6
Christodoulou D. M., Laycock S. G. T., Kazanas D., et al., 2017, RAA, 17, 63
Christodoulou D. M., Laycock S. G. T., Kazanas D., 2018, arXiv:1806.05000 (MNRAS in press)
D’Ai A., Evans P. A., Burrows P. A., et al., 2016, MNRAS, 463, 2394
Dall’Osso S., Perna R., Stella L., 2015, MNRAS, 449, 2144
De Luca A., Caraveo P. A., Mereghetti S., et al., 2006, Science, 313, 814
Doroshenko V., Tsygankov S., Santangelo A., 2018, A&A, 613, 19
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Eksi K. Y., Andac I. C., Cikintoglu S., et al., 2015, MNRAS, 448, L40
Feng H., Soria R., 2011, New Astronomy Reviews, 55, 166
Frank J., King A., Raine D., 2002, Accretion power in astrophysics, Cambridge University Press, Cambridge
Fürst F., Walton D. J., Harrison F. A., et al., 2016, ApJ, 831, L14
Gonzalez-Galan A., Oskinova L. M., Popov S. B., et al., 2018, MNRAS, 475, 2809
Ghosh P., Lamb F. K., 1979, ApJ, 234, 296
Ho W. C. G., Klus H., Coe M. J., et al., 2014, MNRAS, 437, 3664
Hu C. P., Chou Y., Ng C. Y., et al., 2017, ApJ, 844, 16
Israel G. L., Papitto A., Esposito P., et al., 2017a, MNRAS, 466, L48
Israel G. L., Belfore A., Stella L., 2017b, Science, 355, 817
Kaspi V. M., Beloborodov A. M., 2017, ARA&A, 55, 261
Kennel J. A., Lien A. Y., Krimm H. A., et al., 2017, The Astronomer’s Telegram, 10809
King A., Lasota J. P., Kluzniak W., 2017, MNRAS, 468, L59
Klus H., Ho W. C. G., Coe M. J., et al., 2014, MNRAS, 437, 3863
Lai D. 2014, arXiv:1402.1903
Menou K., Esin A. A., Narayan R., et al., 1999, ApJ, 520, 276
Mereghetti S., Pons J. A., Melatos A., 2015, Space Sci Rev, 191, 315
Mushtukov A. A., Suleimanov V. F., Tsygankov S. S., et al., 2015, MNRAS, 454, 2539
Paczynski B., 1992, ACTA ASTRONOMICA, 42, 145
Pan Y. Y., Song L. M., Zhang C. M., et al., 2016, MNRAS, 461, 2
Pintore P., Zampieri L., Stella L., et al., 2017, ApJ, 836, 113
Rea N., Esposito P., Turolla R., et al., 2010, Science, 330, 944
Rea N., Borehese A., Esposito P., et al., 2016, ApJ, 828, L13
Reig P., Torrejon J. M., Blay P., 2012, MNRAS, 425, 595
Revnivtsev M., Mereghetti S., 2015, Space Sci Rev, 191, 293
Sanjurjo-Ferrin G., Torrejon J. M., Postnov K., et al., 2017, A&A, 606, A145
Shapiro S. L., Teukolsky S. A., 1983, “Black holes, white dwarfs, and neutron stars”, John Wiley & Sons, New York
Sidoli L., 2017, Proceedings of the XII Multifrequency Behaviour of High Energy Cosmic Sources Workshop. 12-17 June, 2017 Palermo, Italy, id 52
Sidoli L., Israel G. L., Esposito P., et al., 2017, MNRAS, 469, 3056
Shibazaki N., Murakami T., Shaham J., et al., 1989, Nature, 342, 656
Suğizaki M., Hihara T., Nakajima M., et al., 2017, PASJ, 69, 100
Teng A., Esposito P., Mereghetti S., et al., 2013, Nature, 500, 312
Tong H., Xu R. X., 2012, ApJ, 757, L10
Tong H., Wang W., 2014, arXiv:1406.6458
Tong H., 2015, RAA, 15, 517
Tong H., Wang W., Liu X. W., et al., 2016, ApJ, 833, 265
Tsygankov S. S., Mushtukov A. A., Suleimanov V. F., et al., 2016, MNRAS, 457, 1101
Turolla R., Zane S., Pons J. A., et al., 2011, ApJ, 740, 105
Wang W., 2009, MNRAS, 398, 1428
Wang W., 2011, MNRAS, 413, 1083
Wang W., 2013, MNRAS, 432, 954
Walter R., Lutovinov A. A., Bozzo E., et al., 2015, Astro. Astrophys. Rev., 23, 2
Walton D. J., Fürst F., Heida M., et al., 2018a, ApJ, 856, 128
Walton D. J., Bachetti M., Fürst F., et al., 2018b, ApJL, 857, L3
Woods P. M., Thompson C., 2006, “Soft gamma repeaters and anomalous X-ray pulsars: magnetar candidates”, in Compact stellar X-ray sources, ed. W. Levin & M. van der Klis, Cambridge University Press, Cambridge
Yang J., Laycock S. G. T., Christodoulou D. M., et al., 2017, ApJ, 839, 119
Zhou P., Chen Y., Li X. D., et al., 2014, ApJ, 781, L16
Zhang C. M., Kojima Y., 2006, MNRAS, 366, 137