

# An accreting low magnetic field magnetar for the ultraluminous X-ray source in M82 \*

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**Abstract** One ultraluminous X-ray source in M82 has recently been identified as an accreting neutron star (named NuSTAR J095551+6940.8). It has a super-Eddington luminosity and is spinning up. An aged magnetar is more likely to be a low magnetic field magnetar. An accreting low magnetic field magnetar may explain both the super-Eddington luminosity and the rotational behavior of this source. Considering the effect of beaming, the spin-up rate is understandable using the traditional form of accretion torque. The transient nature and spectral properties of M82 X-2 are discussed. The theoretical range of periods for accreting magnetars is provided. Three observational appearances of accreting magnetars are summarized.

**Key words:** accretion — pulsars: individual (NuSTAR J095551+6940.8) — stars: magnetars — stars: neutron

## 1 INTRODUCTION

Pulsars are rotating magnetized neutron stars. Up to now, various kinds of pulsar-like objects have been discovered (Tong & Wang 2014). Among them are: normal pulsars whose surface dipole field is about  $10^{12}$  G (e.g. the Crab pulsar, Wang et al. 2012); high magnetic field pulsars with surface dipole field as high as  $10^{14}$  G (Ng & Kaspi 2011); central compact objects whose surface magnetic field is at the lower end, about  $10^{10}$  G (Gotthelf et al. 2013). Millisecond pulsars are thought to recycled neutron stars (Alpar et al. 1982). Their surface dipole fields may have decreased significantly during the recycling process (Zhang & Kojima 2006), which can be as low as a few times  $10^8$  G. Magnetars are thought to be neutron stars whose emission is powered by their strong magnetic fields (Duncan & Thompson 1992). Their surface dipole fields can be as high as  $10^{14} - 10^{15}$  G (Tong et al. 2013). At the same time, they may have even higher multipole fields (Tong & Xu 2011, 2014). For an aged magnetar, its dipole magnetic field may have decreased a lot ( $\sim 10^{12}$  G, Turolla et al. 2011). At the same time, their surface multipole fields may still be in the range for a magnetar (i.e. a “low magnetic field” magnetar). Several low magnetic field magnetars are known (Rea et al. 2010, 2012; Zhou et al. 2014).

Accretion powered X-ray pulsars were discovered at the beginning of X-ray astronomy. Since magnetars are just a special kind of neutron star, an accreting magnetar is also expected. However, no strong observational evidence for the existence of an accreting magnetar has been found (Wang

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2013; Tong & Wang 2014). Possible observational signatures of accreting magnetars are discussed in Tong & Wang (2014), including magnetar-like bursts and those with a hard X-ray tail. The recently discovered ultraluminous X-ray pulsar in M82 (NuSTAR J095551+6940.8, Bachetti et al. 2014) may be another manifestation of an accreting magnetar.

Ultraluminous X-ray sources are commonly assumed to be accreting black holes (with either stellar mass or intermediate mass, Liu et al. 2013; Feng & Soria 2011). The discovery of a pulsation period and spin-up trend of an ultraluminous X-ray source in M82 points to an accreting neutron star (Bachetti et al. 2014). The neutron star's X-ray luminosity can be as high as  $10^{40} \text{ erg s}^{-1}$ , with rotational period 1.37 s and period derivative  $\dot{P} \approx -2 \times 10^{-10}$  (Bachetti et al. 2014). If the central neutron star is a low magnetic field magnetar, an accreting low magnetic field magnetar may explain both the radiative and timing observations.

Model calculations are presented in Section 2, including super-Eddington luminosity (Sect. 2.1) and rotational behaviors (Sect. 2.2). Discussion and conclusions are given in Sections 3 and 4, respectively.

## 2 ACCRETING LOW MAGNETIC FIELD MAGNETAR

### 2.1 Super-Eddington Luminosity

According to Bachetti et al. (2014), the ultraluminous X-ray pulsar NuSTAR J095551+6940.8 has a pulsed luminosity of  $4.9 \times 10^{39} \text{ erg s}^{-1}$  (in the energy range 3–30 keV). However, there is more than one ultraluminous X-ray source in M82 (Kaaret et al. 2006). According to the centroid of the pulsed flux, the ultraluminous X-ray source M82 X-2 may be the counterpart of NuSTAR J095551+6940.8. Soft X-ray observation of M82 X-2 shows the luminosity is  $6.6 \times 10^{39} \text{ erg s}^{-1}$  (in the energy range 0.5–10 keV). Therefore, the total X-ray luminosity of NuSTAR J095551+6940.8 may be (assuming isotropic emission, Bachetti et al. 2014)

$$L_{\text{iso}}(0.5 - 30 \text{ keV}) = L_{\text{iso},40} \times 10^{40} \text{ erg s}^{-1}, \quad (1)$$

where  $L_{\text{iso},40} \approx 1$ . For an accreting neutron star, the dipole magnetic field will channel the accreted material into columns near the star's polar cap (Shapiro & Teukolsky 1983). Therefore, the emission of the neutron star is expected to be beamed (Gnedin & Sunyaev 1973). The true X-ray luminosity should be corrected by a beaming factor

$$L_{\text{x}}(0.5 - 30 \text{ keV}) = b L_{\text{iso}} = b L_{\text{iso},40} \times 10^{40} \text{ erg s}^{-1}, \quad (2)$$

where  $b < 1$  is the beaming factor. From previous pulse profile observations of accreting neutron stars (figure 7 in Bildsten et al. 1997), there should be some amount of beaming<sup>1</sup>. If the duty cycle of the pulse profile is about 50%, then the solid angle of the radiation beam may only occupy 25% of the whole sky<sup>2</sup>. In the following, a beaming factor of  $b = 0.2$  is chosen (or  $b^{-1} = 5$ , consistent with other observational constraints, Feng & Soria 2011).

#### 2.1.1 Accreting normal neutron star

The maximum luminosity for steady spherical accretion is (i.e. the Eddington limit, Frank et al. 2002)

$$L_{\text{Edd}} = 1.3 \times 10^{38} M_1 \text{ erg s}^{-1}, \quad (3)$$

<sup>1</sup> The ultraluminous X-ray pulsar NuSTAR J095551+6940.8 also has some pulse profile information, see figure 1 in Bachetti et al. (2014).

<sup>2</sup> This is a very crude estimation. The beaming factor adopted in the following is essentially an assumption.

where  $M_1$  is the mass of the central star in units of solar masses. Considering the modification due to the accretion column, the maximum luminosity for an accreting neutron star is several times higher (Basko & Sunyaev 1976, denoted as the critical luminosity in the following)

$$L_{\text{cr}} = \frac{l_0}{2\pi d_0} L_{\text{Edd}} = 8 \times 10^{38} \left( \frac{l_0/d_0}{40} \right) M_1 \text{ erg s}^{-1}, \quad (4)$$

where  $l_0$  is the length of the accretion column and  $d_0$  is the thickness. The typical value of  $l_0/d_0$  is about 40 (Basko & Sunyaev 1976). Both theory and observation of neutron stars show that they may have a mass in excess of 1.4 solar masses (e.g. 2 solar masses) (Lai & Xu 2011 and references therein). The existence of two solar mass neutron stars may be difficult to understand compared with other neutron star mass measurements (Zhang et al. 2011). One way to form heavy neutron stars may involve super-Eddington accretion (Lee & Cho 2014). Since NuSTAR J095551+6940.8 is probably accreting at a super-Eddington rate, it may also have a larger mass. If the central neutron star is massive<sup>3</sup> with  $M_1 = 2$ , the theoretical maximum luminosity is  $L_{\text{cr}} = 1.6 \times 10^{39} \left( \frac{l_0/d_0}{40} \right) \text{ erg s}^{-1}$ . For a beaming factor  $b = 0.2$ , the true X-ray luminosity is  $L_{\text{x}} = 2 \times 10^{39} L_{\text{iso},40} \text{ erg s}^{-1}$ . Therefore, it cannot be ruled out that the central neutron star of NuSTAR J095551+6940.8 is a massive neutron star (with no peculiarity in its magnetic properties). Meanwhile, for an accreting massive neutron star, the maximum apparent isotropic luminosity will be in the range  $10^{40} \text{ erg s}^{-1}$ . It is very hard to reach a luminosity higher than  $10^{40} \text{ erg s}^{-1}$ . In this case, NuSTAR J095551+6940.8 will be an extreme example of an accreting normal neutron star.

### 2.1.2 Accreting magnetar

The super-Eddington luminosity is easier to understand in the magnetar case. Magnetars can have giant flares due to a sudden release of magnetic energy. In the pulsating tail, the star's luminosity can be as high as  $10^{42} \text{ erg s}^{-1}$ , lasting for about hundreds of seconds (Mereghetti 2008). One of the reasons to propose the magnetar idea is to explain this super-Eddington luminosity (Paczynski 1992). The same argument can also be applied to the ultraluminous X-ray pulsar in M82. The scattering cross section between electrons and photons is significantly suppressed in the presence of a strong magnetic field (only for one polarization). In order to obtain the corresponding critical luminosity, some average (e.g. Rosseland mean) of cross section (or opacity) is needed. The final result is (Paczynski 1992)

$$\frac{L_{\text{cr}}}{L_{\text{Edd}}} \approx 2 \times \left( \frac{B}{10^{12} \text{ G}} \right)^{4/3}, \quad (5)$$

which is only valid for  $L_{\text{cr}} \gg L_{\text{Edd}}$ . If the total magnetic field near the polar cap<sup>4</sup> is  $10^{14} \text{ G}$ , then the critical luminosity is  $L_{\text{cr}} \approx 10^3 L_{\text{Edd}} \approx 10^{41} \text{ erg s}^{-1}$ . Considering the geometry of the accretion column, the critical luminosity may be even higher (Basko & Sunyaev 1976). In the case of an accreting magnetar, even the most luminous sources with a luminosity as high as  $10^{41} \text{ erg s}^{-1}$  are possible. Therefore, the ultraluminous X-ray pulsar in M82 with isotropic luminosity of about  $10^{40} \text{ erg s}^{-1}$  can be safely understood in the accreting magnetar case.

## 2.2 Rotational Behaviors

The ultraluminous X-ray pulsar NuSTAR J095551+6940.8 has a rotational period of  $P = 1.37 \text{ s}$  (Bachetti et al. 2014). At the same time, the pulsar is spinning up (i.e. the rotational period is decreasing). The period derivative is roughly about  $\dot{P} \approx -2 \times 10^{-10}$  (Bachetti et al. 2014). For this

<sup>3</sup> The following conclusions are unaffected by a different choice of central neutron star mass, e.g.  $M_1 = 1.4$ .

<sup>4</sup> Here only the total magnetic field strength near the polar cap is required. No specific magnetic field geometry is assumed.

accreting neutron star, its light cylinder radius is (where the rotational velocity equals the speed of light)  $R_{lc} = \frac{Pc}{2\pi} = 6.5 \times 10^9$  cm. The corotation radius is defined as where the local Keplerian velocity equals the rotational velocity

$$R_{co} = \left( \frac{GM}{4\pi^2} \right)^{1/3} P^{2/3} = 1.8 \times 10^8 M_1^{1/3} \text{ cm}, \quad (6)$$

where  $G$  is the gravitational constant. In the presence of a magnetic field, the accretion flow will be controlled by the magnetic field. The Alfvén radius characterizes this quantitatively. It is defined as the radius where the magnetic energy density equals the kinetic energy density of the accretion flow (Shapiro & Teukolsky 1983; Lai 2014)

$$R_A = 3.2 \times 10^8 \mu_{30}^{4/7} M_1^{-1/7} \dot{M}_{17}^{-2/7} \text{ cm}, \quad (7)$$

where  $\mu_{30}$  is the dipole magnetic moment in units of  $10^{30}$  G cm<sup>3</sup> and  $\dot{M}_{17}$  is the mass accretion rate in units of  $10^{17}$  g s<sup>-1</sup> (the corresponding luminosity is about  $10^{37}$  erg s<sup>-1</sup>). When the Alfvén radius is smaller than the light cylinder radius, the accretion flow may interact with the central neutron star. In the case of spin equilibrium, the Alfvén radius is equal to the corotation radius (Lai 2014). NuSTAR J095551+6940.8 may be in spin equilibrium ( $|P/\dot{P}| \approx 200$  years). However, its counterpart M82 X-2 is a transient source (Feng & Kaaret 2007; Kong et al. 2007). Therefore, whether or not it is in spin equilibrium is not certain (i.e. which luminosity corresponds to the spin equilibrium case is not known). The measurement of period derivative for this source means that the star is experiencing some accretion torque. From this point, the star's dipole magnetic field may be determined. Whether or not the star is in spin equilibrium can be subsequently checked.

For the X-ray luminosity in Equation (2), the corresponding accretion rate onto the neutron star is

$$\dot{M}_{acc} = \frac{R}{GM} L_x = 7.5 \times 10^{19} b L_{iso,40} R_6 M_1^{-1} \text{ g s}^{-1}, \quad (8)$$

where  $M$  is the mass of the neutron star,  $R$  is the radius of the neutron star and  $R_6$  is the radius in units of  $10^6$  cm. The corresponding Alfvén radius is

$$R_A = 4.8 \times 10^7 \mu_{30}^{4/7} M_1^{1/7} (b L_{iso,40} R_6)^{-2/7} \text{ cm}. \quad (9)$$

The angular momentum carried onto the neutron star by the accreted matter is (Shapiro & Teukolsky 1983, which follows the treatment of Ghosh & Lamb 1979; Lai 2014):  $\dot{M}_{acc} \sqrt{GM R_A}$ . The angular momentum of the central neutron star is  $J = I\Omega$ , where  $I = 2/5 MR^2$  is the moment of inertia of the neutron star and  $\Omega = 2\pi/P$  is the angular velocity. The change of stellar angular momentum is  $\dot{J} = I\dot{\Omega} = -2\pi I \dot{P}/P^2$  (the change in moment of inertia is negligible, Shapiro & Teukolsky 1983). According to conservation of angular momentum,

$$-2\pi I \frac{\dot{P}}{P^2} = \dot{M}_{acc} \sqrt{GM R_A}. \quad (10)$$

Therefore, the dipole magnetic moment of the neutron star in NuSTAR J095551+6940.8 is

$$\mu_{30} = 2 \times 10^{-4} M_1^5 R_6^4 b^{-3} L_{iso,40}^{-3}. \quad (11)$$

The dipole magnetic moment is related to the polar magnetic field as  $\mu = 1/2 B_p R^3$  (Shapiro & Teukolsky 1983; Tong et al. 2013). The corresponding magnetic field at the neutron star's polar cap is

$$B_p = 4 \times 10^8 M_1^5 R_6 b^{-3} L_{iso,40}^{-3} \text{ G}. \quad (12)$$

For a two solar mass neutron star ( $M_1 = 2$ ) with a beaming factor  $b = 0.2$ , the dipole magnetic field is about  $B_p = 1.6 \times 10^{12} R_6 L_{iso,40}^{-3}$  G. Combined with the super-Eddington luminosity requirement,

the central neutron star is likely to be a low magnetic field magnetar. The star's high multipole field near the surface (about  $10^{14}$  G) accounts for the super-Eddington luminosity. The much lower dipole field (about  $10^{12}$  G) is responsible for rotational behaviors. From an evolutionary point of view, an aged magnetar is also more likely to be a low magnetic field magnetar (Turolla et al. 2011).

Since M82 X-2 (the possible counterpart of NuSTAR J095551+6940.8) is highly variable, its peak luminosity can reach  $2.2 \times 10^{40}$  ergs $^{-1}$  (Feng & Kaaret 2007). In its low state, the source is below the detection limit, with luminosity lower than  $10^{37}$ – $10^{38}$  erg s $^{-1}$  (Feng & Kaaret 2007; Kong et al. 2007, different authors have given different estimations). Whether NuSTAR J095551+6940.8 is in spin equilibrium is determined by the long term average mass accretion rate, which is unfortunately not known precisely at present. Considering the variation of X-ray luminosity, the average accretion rate can be in the range  $10^{17}$ – $10^{20}$  g s $^{-1}$ . The equilibrium period can be determined by setting the corotation radius and the Alfvén radius equal (Lai 2014)

$$P_{\text{eq}} = 3.1 \mu_{30}^{6/7} M_1^{-5/7} \dot{M}_{\text{ave},17}^{-3/7} \text{ s}, \quad (13)$$

where  $\dot{M}_{\text{ave},17}$  is average accretion rate in units of  $10^{17}$  g s $^{-1}$ . Substituting the magnetic moment in Equation (11), the equilibrium period of NuSTAR J095551+6940.8 is  $P_{\text{eq}} = 2 \times 10^{-3} M_1^{25/7} R_6^{24/7} b^{-18/7} L_{\text{iso},40}^{-18/7} \dot{M}_{\text{ave},17}^{-3/7}$  s. For typical parameters,  $M_1 = 2$  and  $b = 0.2$ , the corresponding equilibrium period is  $P_{\text{eq}} = 1.6 R_6^{24/7} L_{\text{iso},40}^{-18/7} \dot{M}_{\text{ave},17}^{-3/7}$  s. If the long term average accretion rate of NuSTAR J095551+6940.8 is approximately  $10^{17}$  g s $^{-1}$ , then it may be in spin equilibrium (with a current period of 1.37 s). If the long term average accretion rate is  $10^2$  ( $10^3$ ) times higher, the equilibrium period will be about 0.2 s (0.1 s). Then the neutron star is not in spin equilibrium and should experience some kind of net spin up. This is also consistent with observations (with period derivative  $-2 \times 10^{-10}$ ). According to current knowledge, both cases are possible.

### 3 DISCUSSION

#### 3.1 Transient Nature

If M82 X-2 is indeed the counterpart of NuSTAR J095551+6940.8, then more information is available. M82 X-2 is a transient source. Its luminosity ranges from  $10^{40}$  erg s $^{-1}$  to lower than  $10^{37}$ – $10^{38}$  erg s $^{-1}$  (Feng & Kaaret 2007; Kong et al. 2007). One possibility is that the neutron star switches between the accretion phase and the propeller phase (Cui 1997). If the neutron star is near spin equilibrium (the Alfvén radius is approximately equal to the corotation radius), a higher accretion rate will result in a higher X-ray luminosity (accretion phase and spin-up). When the accretion rate is lower, the Alfvén radius will be larger (see Eq. (7)). Then the centrifugal force will be larger than the gravitational force. The amount of accreted matter that can fall onto the neutron star will be greatly reduced (the propeller phase and spin-down). A much lower X-ray luminosity is expected in the propeller phase, as has been observed in other accreting neutron star systems (Cui 1997; Zhang et al. 1998). The transient nature of M82 X-2 may due to switches between the accretion phase and the propeller phase.

#### 3.2 Spectral Properties

There may be a disk component in the soft X-ray spectra of M82 X-2 (at the  $4.1\sigma$  significance level, Feng et al. 2010). The inner disk radius is about  $3.5_{-1.9}^{+3.0} \times 10^9$  cm (90% confidence level). The inner disk temperature is about  $0.17 \pm 0.03$  keV (Feng et al. 2010). According to the above calculations, the typical Alfvén radius is about  $7.5 \times 10^7 R_6^2 L_{\text{iso},40}^{-2}$  cm (by substituting Eq. (11) into Eq. (9)). For a standard thin disk, the disk temperature at the Alfvén radius is about 0.15 keV (using eq. (5.43) in Frank et al. 2002). For an accreting neutron star the Alfvén radius may be the inner disk radius (Lai

2014). However, the observed inner disk radius is very uncertain. The theoretical temperature at the Alfvén radius is consistent with the observed inner disk temperature. A future determination of the disk radius that is more accurate may constrain this model (and other models, see below).

### 3.3 Range of Periods for an Accreting Magnetar

From Equation (13), the equilibrium period ranges from about 0.1 s to several seconds for an accreting low magnetic field magnetar (with dipole field about  $10^{12}$  G). The exact value is determined by the long term average mass accretion rate. If the surface dipole field for some accreting magnetars is still very high (the extreme value is  $10^{15}$  G), then the corresponding equilibrium period can be as high as  $10^3$  s. Therefore, the range of period for accreting magnetars may extend from 0.1 s to  $10^3$  s. If the orbital period is about several days as in the case of NuSTAR J095551+6940.8, the timescale of X-ray observations (tens of kiloseconds) will be a significant fraction of the orbital period. An accelerated searching technique must be employed in order to identify these periodic pulsations (Bachetti et al. 2014).

### 3.4 Observational Appearances of Accreting Magnetars

The discovery of low magnetic field magnetars (with a dipole field a few times  $10^{12}$  G, Rea et al. 2010, 2012; Zhou et al. 2014; Tong & Xu 2012, 2013) clearly demonstrates that a multipole field is a crucial attribute of magnetars. In order to power both persistent emission and bursts, a dipole field is not enough. A stronger multipole field (about or higher than  $10^{14}$  G) is needed. Several failed predictions of the magnetar model (the supernova energy associated with magnetars has a normal value, the non-detection of magnetars by the *Fermi* telescope, etc) have challenged the existence of a strong dipole field in magnetars (Tong & Xu 2011 and references therein). It has been shown that magnetars may exhibit wind braking and a strong dipole magnetic field is not necessary (Tong et al. 2013). The key aspect of magnetars is their strong multipole field. A signature of a strong multipole field is needed in order to say that an accreting magnetar is observed (Tong & Wang 2014). From Equation (13), for an accreting high magnetic field neutron star (with a dipole field higher than  $10^{14}$  G), the equilibrium period will be larger than one hundred seconds. Previously, some super-slow X-ray pulsars were thought to be accreting magnetars (with a pulsation period longer than  $10^3$  s, Wang 2013). However, this is at most observational evidence of a strong dipole field. A neutron star with a strong dipole field is not necessarily a magnetar (Ng & Kaspi 2011). Tong & Wang (2014) discussed possible observational appearances of accreting magnetars. Combined with the result in this paper, three observational appearances of accreting magnetars are available at present: (1) magnetar-like bursts, (2) a hard X-ray tail (higher than 100 keV), and (3) an ultraluminous X-ray pulsar.

### 3.5 Comparison with Other Papers

In the observational paper, Bachetti et al. (2014) made some estimations and showed that it may be difficult to explain both the super-Eddington luminosity and the spin-up rate. Assuming spin equilibrium, the Alfvén radius will be approximately equal to the corotation radius. Not considering the effect of beaming, the luminosity  $10^{40}$  erg s<sup>-1</sup> requires a mass accretion rate of about  $10^{20}$  g s<sup>-1</sup>. According to Equation (10), the theoretical spin-up rate is about  $-6 \times 10^{-9}$ , but the observed spin-up rate is only about  $-2 \times 10^{-10}$ . In order to solve this controversy, Ekşi et al. (2015) and Lyutikov (2014) tried different forms of accretion torque. However, according to the above calculations, the observed spin-up rate is understandable even in the traditional formula of accretion torque provided that the effect of beaming is considered. With only one ultraluminous X-ray pulsar at hand, there are many uncertainties. More observations of more sources are needed in order to clarify this problem.

## 4 CONCLUSIONS

The ultraluminous X-ray pulsar NuSTAR J095551+6940.8 in M82 is modeled as an accreting low magnetic field magnetar. A magnetar-strength multipole field is responsible for the super-Eddington luminosity. The much lower large scale dipole field determines the interaction between the neutron star and the accretion flow. Its rotational behaviors can be explained using the traditional form of accretion torque considering the effect of beaming. The counterpart of NuSTAR J095551+6940.8 (M82 X-2) is a transient because it may switch between the accretion phase and the propeller phase. The theoretical range of period for accreting magnetars may be very wide. Three observational verifications of accreting magnetars are available at present.

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