"High-field" pulsars torqued by accretion disk?

Y. L. Yue, W. W. Zhu, R. X. Xu *

Astronomy Department, School of Physics, Peking University, Beijing 100871, China

Abstract

The nature of AXPs/SGRs (anomalous X-ray pulsars/soft γ-ray repeaters) and high field radio pulsars is still unclear even in the magnetar and/or accretion models. The detection of radio emission from AXP XTE J1810−197 and the discovery of a debris disk around AXP 4U 0142+61 might shed light on the problem. We propose that AXPs/SGRs could be pulsars that have magnetic field \( B \lesssim 10^{13} \) G as normal pulsars, but in accretion environments. We investigate these issues under the accretion model and find that two of the AXPs/SGRs might be low mass quark stars if all AXPs and SGRs are likely grouped together.

Key words: dense matter, pulsars: general, stars: neutron
PACS: 97.60.Gb, 97.60.Jd

1 Introduction

As the number of observed pulsar increasing, there turns to be some pulsars have apparent magnetic field strength \( \gtrsim 10^{14} \) G. These “high field” pulsars (AXPs/SGRs and high field radio pulsars) challenge the physics of matter in strong magnetic field, even being greater than the critical magnetic field \( B_c = m_e^2 c^3 / (e \hbar) \simeq 4.4 \times 10^{13} \) G. The high field radio pulsars can have magnetic fields as high as that of AXPs (two AXPs even have \( B \)-field being stronger than the lowest field of AXPs). Meanwhile, there are several kinds of pulsars that spin at periods \( (P) \) being similar to that of AXPs/SGRs \( (P \sim 10 \) s), such as DTNs (dim thermal neutron stars), part of RRATS (rotating radio transient

* Corresponding author.
Email address: r.x.xu@pku.edu.cn (R. X. Xu).
URL: http://vega.bac.pku.edu.cn/rxxu/ (R. X. Xu).
sources, McLaughlin et al., 2006) and the peculiar pulsar PSR J2144−3933 which seems under the death line (Young et al., 1999). A question rises then: why these pulsar-like stars manifest so differently? The detection of radio emission from AXP XTE J1810−197 (Camilo et al., 2006) and the discovery of a debris disk around AXP 4U 0142+61 (Wang et al., 2006) may show the missing links between AXPs/SGRs and radio pulsars together.

AXPs/SGRs should have very strong magnetic field if their spindown is torqued dominantly by magnetospheric activity. However, whether the fields are really so strong or not is still under debating. There are generally three kinds of models. (i) the magnetar model: the sources to be actually neutron stars with ultra strong magnetic fields $B$ of $10^{14}–10^{15}$ G (e.g. Duncan & Thompson, 1992); (ii) the accretion model: to be normal pulsars with $B \lesssim 10^{13}$ G but with accretion disks (e.g. Alpar, 2001); (iii) the hybrid model: to be neutron stars with ultra strong magnetic fields but also surrounded by accretion disks (e.g. Eksi & Alpar, 2003).

The detection of radio emission (Camilo et al., 2006) from AXP and IR emission from debris disk (Wang et al., 2006) around AXP may favor the accretion disk model. In this article, we investigate the nature of AXPs/SGRs in the regime of accretion model of normal magnetic fields $B \lesssim 10^{13}$ G, considering the sources to be possibly both neutron stars and/or quark stars. We find that the two of the AXPs/SGRs might be low mass quark stars under certain assumptions.

2 AXPs/SGRs as accreting pulsars

In the accretion model, the accretion rate $\dot{M}$ consists two parts: $\dot{M}_{\text{in}}$ which produces the X-ray emission, and $\dot{M}_{\text{out}}$ which results in the accretion torque, i.e. $\dot{M} = \dot{M}_{\text{in}} + \dot{M}_{\text{out}}$. Since the X-ray luminosity from magnetosphere of rotation-powered X-ray pulsars is relatively low, we could assume that the X-ray radiation would be accretion-originated,

$$L_x = \eta \dot{M}_{\text{in}} c^2,$$

where $\eta$ is the matter-to-energy conversion efficiency and $c$ is the speed of light. If the X-ray luminosity comes from release of gravitational energy in case of a normal neutron star ($M \sim 1.4M_\odot$), $\eta \sim 2GM/c^2/R \sim 10\%$, where $G$ is the gravitational constant $M$ is the stellar mass and $R$ is the stellar radius; while if it comes from the phase transition energy from baryons to quarks in case of quark stars (even with low masses, (Xu, 2005)), $\eta \sim 100$ MeV/930 MeV $\sim 10\%$. For massive quark stars ($M \sim 1.4M_\odot$), both gravitational energy and
phase transition energy should be considered, i.e., \( \eta \sim 20\% \). The difference is only by a factor of 2. Considering the uncertainty of the estimated efficiency, we use \( \eta = 10\% \) for all the cases below.

For a quark star with mass smaller than \( 1.4M_\odot \), the magnetic field could be expressed as,

\[
B \simeq 6.4 \times 10^{19}(P\dot{P})^{1/2}\left(\frac{M}{1.4M_\odot}\right)^{1/2}\left(\frac{R}{10 \text{ km}}\right)^{-2} \text{G},
\]

(2)

where \( P \) is the spin period and \( \dot{P} \) is the period derivative. The density of low mass quark stars could almost be a constant (Alcock et al., 1986), \( \rho \sim 4\bar{B} \), where \( \bar{B} \sim 60–110 \text{ MeV fm}^{-3} \) (1.1–2.0 \times 10^{14} \text{ g cm}^{-3}) is the bag constant in the MIT bag model. The median value \( \rho \sim 6 \times 10^{14} \) is about 2 times the nuclear saturation density \( \rho_n (= 2.7 \times 10^{14} \text{ g cm}^{-3}) \), and is also close to the mean density of a normal neutron star with \( M = 1.4M_\odot \) and \( R = 10 \text{ km} \) (\( \bar{\rho} = 6.7 \times 10^{14} \text{ g cm}^{-3} \)). Thus we may approximate the density \( \sim 4\bar{B} \) for a 1.4\( M_\odot \) neutron star. The magnetic field could then be

\[
B \simeq 6.4 \times 10^{19}(P\dot{P})^{1/2}\left(\frac{R}{10 \text{ km}}\right)^{-1/2} \text{G}.
\]

(3)

The radius \( R \) could be much smaller than 10 km if pulsar-like stars are actually quark stars (see, e.g., Xu (2006a,b) for more backgrounds and discussion about quark stars).

Though the accretion torque in a propeller phase is still not certain yet, it could also be summarized as (e.g., Jiang & Li, 2005)

\[
T = -\dot{M}_{\text{out}}r_m^2\Omega_K(r_m)\left[\frac{\Omega}{\Omega_K(r_m)}\right]^\gamma,
\]

(4)

where \( r_m \) is the magnetospheric radius (Alfvén radius),

\[
r_m \simeq \left(\frac{B^2R^6}{M\sqrt{2GM}}\right)^{2/7},
\]

(5)

\( \Omega = 2\pi/P, \Omega_K(r_m) \) is the Keplerian angular velocity at \( r_m \) and \( \gamma= -1 \) to 2 corresponding to different accretion models. Another way of parameterizations proposed by Menou et al. (1999) is

\[
T = -2\dot{M}r_m^2\Omega_K(r_m)[1 - \frac{\Omega}{\Omega_K(r_m)}].
\]

(6)
Here we only use Eq. (4) since Eq. (6) does not give information about $\dot{M}_{\text{in}}$ and cannot be connected with $L_x$. In our calculation, we consider both angular momentum added from $\dot{M}_{\text{in}}$ and angular momentum lost from $\dot{M}_{\text{out}}$, thus

$$T = I\dot{\Omega} = \dot{M}_{\text{in}}r_m^2\Omega_K(r_m) - \dot{M}_{\text{out}}r_m^2\Omega_K(r_m)\left[\frac{\Omega}{\Omega_K(r_m)}\right]^\gamma.$$  \hspace{1cm} (7)

In this case, $r_m$ should around co-rotating radius $r_{co} = \left[\frac{GMP^2}{(4\pi^2)}\right]^{1/3}$ and $\dot{M}_{\text{out}}$ should be of the same order of $\dot{M}_{\text{in}}$. We use $r_m/r_{co}$ as a free parameter in the range 0.3–3 and $\dot{M}_{\text{in}}/\dot{M}$ as another free parameter in the range 1–7. On the grid, we calculate the theoretical value of $\dot{\Omega}$ from Eq. (7) and compare it with the observational values. The data are from Woods & Thompson (2006). We use the larger value if the value of a parameter (e.g., $\dot{P}$) varies in a range. There is 8 available stars that has $P$, $\dot{P}$, $L_x$, black-body temperature and distance simultaneously. The results are presented in Fig. (1). We find that two of the AXs/SGRs could be low-mass quark stars in order to have all the stars in a likely same group. If we apply $1.4M_\odot$ and 10 km for all the stars, these two would not be grouped into that of others. The radius of SGR 1099+14 could be $R \sim 5$ km and that of AXP 1E 1048.1-5937 could be $R \sim 2$ km, respectively. These values should not be very exact since the values could vary in a certain range in order to group all the stars. The uncertainty is about 1 km. We have $B \lesssim 10^{13}$ G at all available points in the parameter space.

3 Conclusion and discussion

We discussed the possible accretion environments around the long period pulsars and the supports from observations. They could be understood in a uniform accretion model, in which the requirement of high magnetic field is removed. SGR 1099+14 and AXP 1E 1048.1-5937 might be quark stars of $R \sim 5$ km and $R \sim 2$ km, respectively, under certain assumptions.

The braking index is a good parameter to test torque models (and emission models) since it is an induced parameter directly from observation and depends on less assumption. As a result of observational difficulties, braking indices of only six rotation-powered pulsars are obtained (Livingstone et al. 2006, and references therein). No AXP/SGR has measured good braking index due to the high timing noisy. Because accretion would add additional torque to spin-down, the braking index departs from $n = 3$, e.g. in Chen & Li (2006), varying in the range of $-4$ to $3$ in the accretion model. At the same time, accretion would result in a frequent change of $\dot{P}$. Therefore, the braking index obtained by short-time observation might not be good, to be contaminated dominantly by timing noise. Additionally, the braking index of an accreting pulsar could
also be variable, depending on the accretion state. While, good braking indices of six solitary radio pulsars with no accretion are all in the range of 1 to 3.

The the accretion torque that we use is simply an approximation. The detail coupling between accreted matter and magnetosphere is still not clear. The interaction region could not be a thin layer at $r_m$ but have a certain depth. So the thin layer approximation needs further investigation (via, e.g., numerical simulation).

References

Alcock, C., Farhi, E., & Olinto, A. 1986, ApJ, 310, 261
Alpar, M. A. 2001, ApJ, 554, 1245
Camilo, F., Ransom S., Halpern J. et al. 2006, Nature, 442, 892
Chen, W. C., & Li, X. D. 2006, A&A, 450, L1
Duncan, R.C., & Thompson, C., 1992, ApJ, 392, L9
Ekşi, K. Y., & Alpar, M. A., 2003, ApJ, 599, 450
Jiang, Z. B., & Li, X. D. 2005, ChJAA, 5, 487
Livingstone, M. A., Kaspi, V. M., Gotthelf, E. V., & Kuiper, L. 2006, ApJ, 647, 1286
Menou, K., Esin, A. A., Narayan, R., Garcia, M. R., Lasota, J.-P., & McClintock, J. E. 1999, ApJ, 520, 276
McLaughlin, M. A., Lyne, A. G., Lorimer, D. R., Kramer, M., & Faulkner, A. J. 2006, Nature, 439, 817
Ruderman, M. 2005, preprint (astro-ph/0510623)
Wang, Z., Chakrabarty, D., & Kaplan, D. L. 2006, Nature, 440, 772
Woods, P. M., & Thompson, C. 2006, in: Compact Stellar X-ray Sources, eds. W.H.G. Lewin and M. van der Klis, (Cambridge University Press, UK), preprint (astro-ph/0406133)
Young, M. D., Manchester, R. N., & Johnston, S. 1999, Nature, 400, 848
Xu, R. X. 2005, MNRAS, 356, 359
Xu, R. X. 2006a, Advances in Space Research, 37, 1992
Xu, R.X. 2006b, in: The proceedings of the 2005 Lake Hanas International Pulsar Symposium, in press
Fig. 1. The parameter space for $\gamma = -1$ (dotted), 0 (dashed), 1 (dash-dotted), and 2 (solid). We draw the ratio of total accretion rate ($\dot{M}$) to the rate of accreting onto the star’s surface ($\dot{M}_{\text{in}}$) as a function of the ratio of the Alfvén radius ($r_m$) to the co-rotating radius ($r_{\text{co}}$). Every single line represents a pulsar. On the line, theoretical value of $\dot{P}$ equals to observational one. For $r_m/r_{\text{co}} \sim 1$, all the accretion torque cluster together. In other region, the four models are quite different. In this figure, SGR 1099+14 and AXP 1E 1048.1-5937 are in quark star model, with $R = 5$ km and $R = 2$ km respectively in order to make all the stars appear in a likely same group. For all the available points on the lines, we have $\lesssim 10^{13}$ G.