Evolution implications of neutron star magnetic fields: inferred from pulsars and cyclotron lines of HMXBs

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Abstract The evolution of neutron star (NS) magnetic field (B-field) has long been an important topic, which is still not yet settled down. Here, we analyze the NS B-fields inferred by the cyclotron resonance scattering features (CRSFs) for the high mass X-ray binaries (HMXBs) and by the magnetic dipole model for the spin-down pulsars. We find that the B-fields of both the 32 NS-HMXBs and 28 young pulsars with the supernova remnants follow the log-normal distributions, with the average values of $3.4 \times 10^{12}$ G and $4.1 \times 10^{12}$ G respectively, which are further verified to come from the same continuous distribution by the statistical tests. These results declaim that the two methods of measuring NS B-fields are reliable for the above two groups of samples. In addition, since the NS-HMXBs have experienced the spin-down phase as the normal pulsars without accretion and then the spin-up phase by accretion, their ages should be about million years (Myrs). Our statistical facts imply that the B-fields of NS-HMXBs have little decayed in their non-accretion spin-down phases of $\sim$ Myrs, as well as in their accretion phases of $\sim$0.1 Myrs.

Keywords X-rays: binaries · Stars: neutron · Pulsars: general · Magnetic field

1 Introduction

The magnetic fields (B-fields) of neutron stars (NSs) play the significant roles in many aspects of pulsar phenomena, e.g., the electromagnetic emissions from the radio to high energy wavebands (Harding and Kalapotharakos 2017; Manchester 2017; Becker et al. 2018). Until now, more than 2700 radio pulsars (Lorimer et al. 2019) and over 300 accreting NSs in high/low mass X-ray binaries (HMXBs/LMXBs) (Liu et al. 2007; Walter et al. 2015) have been observed. It is generally accepted that the B-fields of NSs dramatically decay in the binary accretion phase, while those of the isolated NSs should not decay, based on which the low B-field distributions of the double NSs ($B \sim 10^9$–$10^{10}$ G, see Yang et al. 2019) and millisecond pulsars (MSPs, $B \sim 10^{7.5}$–$10^9$ G, see Pan et al. 2018) are very well understood by the binary accretion (Bhattacharya and van den Heuvel 1991; Zhang 2016; van den Heuvel 2017). However, there are still debated issues on the evolutions of NS B-fields: In what extent the B-fields of the isolated NSs have no decay? If the B-fields decay in the accretion phase, can we estimate the extent of the decay for NSs in HMXBs as an inverse relation to the accretion mass proposed (Shibazaki et al. 1989; Kulkarni 1986; Zhang and Kojima 2006)? To answer the above questions, one could evaluate the evolution mechanism of NS B-fields, e.g., the Ohmic dissipation (Geppert and Urpin 1994), Hall-drift effect (Geppert and Rheinhardt 2002; Cumming et al. 2004), screening by diamagnetism of accreting matter (Cumming et al. 2001; Lovelace et al. 2005), and accretion flow to cause the B-field decay (van den Heuvel and Bitzaraki 1995; Melatos and Phinney 2001; Konar and Choudhuri 2004; Payne and Melatos 2004; Zhang and Kojima 2006).

There exist the two methods for measuring the NS B-fields, the magnetic dipole model for the spin-down...
pulsars (Lyne and Graham-Smith 2012), and cyclotron resonance scattering features (CRSFs) for NS-HMXBs (Mészáros 1992). To evaluate the B-field evolution of NSs, we should have the good measurements of both the B-fields and their ages, the young pulsars with the supernova remnants (SNRs) and old NSs in HMXBs. The age of SNR pulsar is less than 0.3 million years (Myrs) (Ferrand and Safi-Harb 2012), which may retain the B-field distribution similar to those as they are born, whereas the NSs in HMXBs have experienced the spin-down and accretion induced spin-up phase with the age of \( \sim \) Myrs. Thus, the comparison of B-fields of both groups could acquire the information of B-field evolutions of NSs.

This paper aims to probe the NS B-field evolution of NS-HMXBs and SNR pulsars by comparing their B-field distributions, inferred by CRSFs and by magnetic dipole model, respectively. The structure of the paper is organized as follows: In Sect. 2, we introduce the B-field data of NS-HMXBs and SNR pulsars. In Sect. 3, we analyze the B-field distributions of the two group of samples, where the statistical tests are performed to see their properties. Finally, we present the discussions and conclusions in Sect. 4.

2 Two methods of NS magnetic field measures

2.1 B-fields of NS-HMXBs by CRSFs

For the accretion powered X-ray pulsars in HMXBs, NSs emit X-rays (e.g., \( \sim 1–100 \) keV) by accreting matters from their companions (Caballero and Wilms 2012; Walter et al. 2015). In the strong B-field regime of NS surface, the electron energy is quantized to the discrete Landau levels, which experiences the resonance scattering with photons and results in the absorption features in the X-ray energy spectrum (Trüemper et al. 1978), i.e., the energy of CRSFs:

\[
E_c = \frac{\hbar}{m_e} \frac{eB}{m_e c} = 11.6 \text{ (keV}) \times B_{12}
\]

where \( B_{12} \equiv B_\odot/10^{12} \) G, with the electron mass \( m_e \) and charge \( e \), as well as the speed of light \( c \) and Planck constant \( \hbar \). The CRSFs are generally considered to form around NS surface (Mészáros 1992; Schönherr et al. 2007; Becker et al. 2012), so the observed energy \( E_c \) are gravitationally red-shifted and corrected to

\[
E_n = nE_c = (1 + z) E_{n,\text{obs}}
\]

where \( n \) is the quantum number of the energy level, corresponding to the fundamental and harmonics of CRSF given by \( n = 1, 2, 3, \ldots \), and the parameter \( z \) is the gravitational red-shift expressed as,

\[
z = \frac{1}{\sqrt{1 - \frac{2GM}{Rc^2}}} - 1,
\]

where \( G \) is the Newtonian gravitational constant. For the typical NS mass of \( M = 1.4M_\odot \) and radius of \( R = 10 \) km, the gravitational red-shift parameter is obtained as \( z = 0.3 \) (Shapiro and Teukolsky 1983; Maitra 2017).

We search for the NS-HMXBs which have been detected with CRSFs, and focus on the 32 sources with the confirmed detection. Table 1 lists the CRSF energies (\( E_c \), fundamental and harmonic) and NS spin periods (\( P \)) of these sources that are collected from the published literature (Makishima et al. 1999; Coburn et al. 2002; Caballero and Wilms 2012; Walter et al. 2015). Furthermore, we infer the B-fields of NS-HMXBs by Eqs. (1)–(3) with the CRSFs in Table 1 by assuming they emit around the NS surface (Mészáros 1992; Becker et al. 2012). Figure 1 illustrates the NS B-field versus spin period distribution of the samples.

2.2 B-fields of pulsars by their periods and derivatives

For the spin-down pulsars, their losses of rotational energies is presumed by the magnetic dipole radiation, based on which their B-fields can be derived by their observed spin periods (\( P \)) and derivatives \( \dot{P} \), as given in the references
in the case of perpendicular rotator (Ostriker and Gunn 1969; Manchester and Taylor 1977; Lyne and Graham-Smith 2012):

\[
B = \left( \frac{3Ic^3P\dot{P}}{8\pi^2R^6} \right)^{1/2} \approx 3.2 \times 10^{19}(P\dot{P})^{1/2} \text{ G},
\]  

(4)

where \( I \) and \( R \) stand for the moment of inertia and radius of NS with the conventional values of \( I = 10^{45} \text{ g cm}^2 \) and \( R = 10 \text{ km} \).

In order to investigate the B-field evolution of NSs, we compare the B-field distribution of the NS-HMXBs with that of the young pulsars with SNRs, whose ages are generally less than 0.3 Myr. Until now, there are 61 SNR pulsars have been recorded in ATNF pulsar catalog (Manchester et al. 2005), in which 28 sources share the B-fields in the ranges of \(~10^{12}–10^{13} \text{ G} \) (as compared to those of CRSF sources, see Table 1) that are analyzed in the paper. These samples are labeled in the diagram of B-field versus spin period, as plotted in Fig. 1.

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**Table 1 CRSF energy and inferred B-fields of NS-HMXBs**

| Source (32) | \( E_c \) (keV) | B-field \( \left(10^{12} \text{ G} \right) \) | \( P \) (s) | REFS. 

| Swift J1626.6–5156 | 10 | 1.12 | 15.35 | [1, 1] |
| XMMU J05 | 10 | 1.12 | 61.23 | [2, 33] |
| KS 1947+300 | 12.50 | 1.40 | 18.70 | [3, 34] |
| 4U 0115+634 | 14, 24, 36, 48, 62 | 1.57 | 3.61 | [4, 35] |
| XTEJ1829−098 | 15 | 1.68 | 7.84 | [5, 5] |
| IGR J17544−2619 | 17 | 1.91 | – | [6, 36] |
| 4U 1907+09 | 19, 39 | 2.12 | 343–440 | [7, 37] |
| 4U 1538−52 | 22, 47 | 2.47 | 528–530 | [8, 38] |
| IGR J18179−1621 | 22 | 2.47 | 11.82 | [9, 39] |
| IGRJ18027−2016 | 23 | 2.58 | 139.61 | [10, 40] |
| 2S 1553−542 | 23.50 | 2.63 | 92.7 | [11, 11] |
| Vela X−1 | 25, 50 | 2.80 | 283 | [12, 41] |
| V 0332+53 | 27, 51, 74 | 3.03 | 4.37 | [13, 42] |
| SMC X−2 | 27 | 3.03 | 2.37 | [14, 14] |
| Cep X−4 | 28, 45 | 3.14 | 66.25 | [15, 43] |
| X per | 29 | 3.25 | 835 | [16, 44] |
| IGR J16393−4643 | 29.3 | 3.28 | 904 | [17, 17] |
| Cen X−3 | 30 | 3.36 | 4.82 | [18, 45] |
| J 16493−4348 | 30 | 3.36 | 1093 | [19, 46] |
| RX J0520.5−6932 | 31.50 | 3.53 | 8.03 | [20, 20] |
| RX J0440.9−4431 | 32 | 3.59 | 202.50 | [21, 47] |
| MXB 0656−072 | 33 | 3.70 | 160 | [22, 48] |
| IGR J19294+1816 | 35.50 | 3.98 | 12.43 | [23, 49] |
| XTE J1946+274 | 36 | 4.03 | 15.80 | [24, 50] |
| 4U 1626−67 | 37 | 4.15 | 7.67 | [25, 51] |
| GX 301−2 | 37 | 4.15 | 675–700 | [26, 52] |
| Her X−1 | 39, 73 | 4.37 | 1.24 | [27, 53] |
| MAXI J1409−619 | 44, 73, 128 | 4.93 | 500 | [28, 54] |
| 1A 0535+262 | 45, 100 | 5.04 | 103 | [29, 55] |
| GX 304−1 | 54 | 6.05 | 272 | [30, 56] |
| 1A 1118−615 | 55, 112 | 6.16 | 405–407 | [31, 57] |
| GRO J1008−57 | 76 | 8.52 | 93.60 | [32, 58] |

Note: \( E_c \)—CRSF energy of the fundamental and multiple harmonics; \( P \)—Spin period of NS; 

*: The first reference of each source is for \( E_c \) (for some sources it record the fundamental and multiple harmonics CRSFs observed simultaneously), and the second reference is for \( P \)
### 3 Analysis on the B-field distributions

The NS B-field statistical quantities of the samples, including the range, mean ($\langle B \rangle$), median ($\tilde{B}$) and standard deviation ($\sigma_B$), are obtained and summarized in Table 2. It can be seen that the NS-HMXBs share the similar $\langle B \rangle$ and $\tilde{B}$ values ($\langle B \rangle \sim 3.39 \times 10^{12}$ G and $\tilde{B} \sim 3.27 \times 10^{12}$ G) to those of the SNR pulsars ($\langle B \rangle \sim 4.09 \times 10^{12}$ G and $\tilde{B} \sim 3.60 \times 10^{12}$ G). In order to investigate whether the two group samples of B-fields come from the same continuous distribution, we make the following two steps: (I). testing the two distributions to be the log-normal or not, and (II). testing the two group B-fields to come from the same continuous distribution or not if both distributions follow the log-normal.

(I). Table 3 lists the Shapiro-Wilk (S-W) test results (Corder and Foreman 2009) of the two group B-field samples, from which it can be noticed that the B-fields of both the NS-HMXBs and SNR pulsars are compatible with the log-normal distributions at the 95 percent confidence level. The expressions of the mean and standard deviation of the log-normal distributions are $\langle B \rangle = (28.75 \pm 0.47) \log_e$ (G) for the NS-HMXBs, and $\langle B \rangle = (28.91 \pm 0.52) \log_e$ (G) for the SNR pulsars, respectively.

(II). Furthermore, we take the Kolmogorov-Smirnov (K-S) test (Corder and Foreman 2009) to compare the B-field distributions of the NS-HMXBs and SNR pulsars, and show the results in Table 4, where the consistency of both distributions is obtained at the 95 percent confidence level.

In order to investigate whether the NS B-field decay or evolve in million years, we studied the two distinctive classes of NS samples: NS-HMXBs that are the accretion X-ray binary systems with the ages of $\sim$ Myrs (Bhattacharya and van den Heuvel 1991), and SNR pulsars that are the pulsating objects with the ages of less than 0.3 Myrs (Ferrand and Safi-Harb 2012). The B-fields of the formers are measured directly by CRSFs and those of the latters are derived by the magnetic dipole model. The following facts and conclusions are noticed and obtained:

- The S-W test indicates that the B-fields of both the 32 NS-HMXBs and 28 SNR pulsars follow the log-normal distributions (see Table 3), and the two group B-fields are further verified to come from the same continuous distribution by the K-S test (see Table 4). According to the evo-

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**Table 2** B-field statistics of 32 NS-HMXBs and 28 SNR pulsars

| Category     | Number | Range of B ($\times 10^{12}$ G) | $\langle B \rangle$ | $\tilde{B}$ | $\sigma_B$ |
|--------------|--------|---------------------------------|---------------------|------------|-----------|
| NS-HMXBs     | 32     | $1.12 \sim 8.52$                | 3.39                | 3.27       | 1.58      |
| SNR pulsars  | 28     | $1.11 \sim 9.91$                | 4.09                | 3.60       | 2.14      |

**Table 3** S-W Test Results of NS B-field Distributions

| Category       | Number | $S - W$ ($p$-value) | Reject $H_0$ |
|----------------|--------|--------------------|--------------|
| NS-HMXBs       | 32     | 0.56               | No           |
| SNR pulsar     | 28     | 0.97               | No           |

**Table 4** K-S Test Results of NS B-field Distributions

| Category       | Number | $K - S$ ($p$-value) | Reject $H_0$ |
|----------------|--------|--------------------|--------------|
| NS-HMXBs       | 32     | 0.74               | No           |
| SNR pulsar     | 28     |                    | No           |

**Note:** $H_0$ is the null hypothesis that the data follows a log-normal distribution, with the confidence level parameter $\alpha = 0.05$
It should be noticed that the B-field inferred from the CRSF measurement is the B-field around the NS surface, while the B-field obtained from the measurement of $P$ and $\dot{P}$ values is calculated by considering the energy loss at the NS light cylinder and then extrapolates the field strength back to the star’s surface assuming the flat space-time $1/r^3$ radial dependence of the field. Thus, for the HMXBs, Eq. (2) takes into account gravitational red-shift, while general relativity effects are not taken into consideration for the B-field of isolated pulsars. The different B-field measures for the NS-HMXBs and SNR pulsars present the same distributions, and we declare that the two methods, by the CRSF and magnetic dipole model, are successfully applied to obtain the B-fields around NS surfaces. In general, the CRSF indicates the local B-field around NS surface, while the B-field inferred by the magnetic dipole model represents the large scale value. The similarity of both B-field values might imply that both the measures and selected NS parameters should be in the reasonable regimes, at least valid in the statistical sense.

The B-field evolution mechanism of NS is critical for understanding the emissions and binary interactions of various pulsars, thus our conclusions, based on the B-field measures of different methods and statistical tests, would provide the robust clues or constraints for the time scale of B-field decay.

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