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# High Magnetic Field Rotation-powered Pulsars

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**Abstract.** Anomalous X-ray pulsars and soft gamma repeaters have recently emerged as a unified class of neutron stars, identified by dramatic X-ray and gamma-ray outbursts and via luminous X-ray pulsations, both thought to be powered by the decay of an enormous internal magnetic field. This “magnetar” hypothesis has raised the question of these objects’ physical relationship with conventional rotation-powered pulsars (RPPs). The highest magnetic-field RPPs might therefore be expected to be transition objects between the two populations. The recently reported magnetar-like outburst of PSR J1846–0258, previously thought to be purely rotation-powered, clearly supports this suggestion. Here we review the observational properties of the highest magnetic-field RPPs known, and show some common characteristics that are notable among RPPs, which are plausibly related to their high fields. Using these objects, we consider the evidence for proposed “magneto-thermal evolution” in neutron stars, and argue that while some exists, it is not yet conclusive.

**Keywords:** pulsars: general – stars: neutron – X-rays: stars

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## INTRODUCTION

Since the discovery of radio pulsars some 40 years ago, they have been the standard textbook examples of pulsars: fast-spinning neutron stars converting their rotational energy into electromagnetic radiation and particle winds. Hence, these pulsars are also referred to as rotation-powered pulsars (RPPs). Based on the spin period ( $P$ ) and its time derivative ( $\dot{P}$ ), a number of physical parameters can be derived, including the characteristic age

$$\tau_c \equiv P/2\dot{P} \quad (1)$$

and the spin-down luminosity

$$\dot{E} \equiv 4\pi^2 I \dot{P}/P^3, \quad (2)$$

where  $I = 10^{45} \text{ g cm}^2$  is the assumed moment of inertia of a neutron star. For pure dipole spin-down in vacuum, the surface  $B$ -field at the magnetic equator can be estimated by

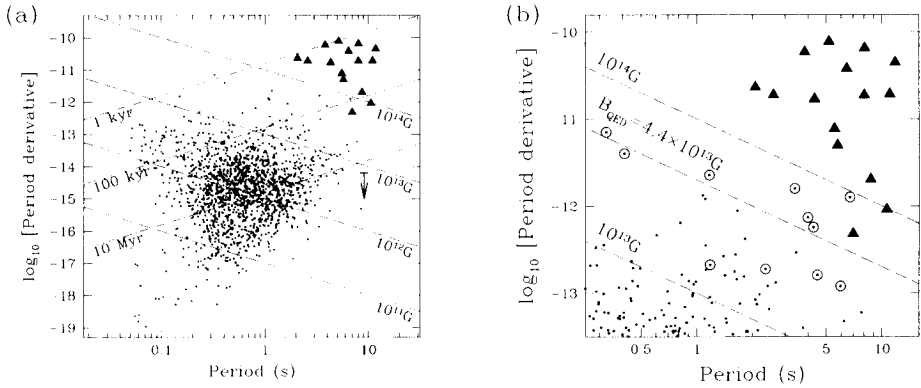
$$B = 3.2 \times 10^{19} \sqrt{P\dot{P}} G, \quad (3)$$

where  $P$  is in s. Note that the field strength at the magnetic poles is higher by a factor of two [1].

RPPs are characterized by their pulsations from radio to MeV  $\gamma$ -rays, with a total radiation power generally less than 1% of  $\dot{E}$ . Young RPPs are often associated with pulsar wind nebulae (PWNe), which provide a unique signature of the pulsar nature

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even if the radio beams miss the Earth. Figure 1a shows the  $P-\dot{P}$  diagram of all isolated RPPs, indicating a typical  $B$ -field around  $10^{12}$  G inferred from the spin parameters.



**FIGURE 1.** (a)  $P-\dot{P}$  diagram of isolated radio pulsars and magnetars, represented by dots and triangles, respectively. The upper limit on  $\dot{P}$  of the magnetar SGR 0418+5729 is shown by the arrow [2]. (b) Zoom-in of the same plot, showing the region containing high- $B$  pulsars and magnetars. Objects listed in Table 1 are marked by the circles.

Over the past two decades, several new classes of neutron stars have been discovered. The most exotic one is magnetars, a small group<sup>2</sup> of isolated X-ray pulsars with long spin periods and large  $\dot{P}$ s that imply ultra-strong surface fields of  $10^{14} - 10^{15}$  G (see review by E. Göğüş in this Volume). This field strength is well above the so-called “quantum critical field” of

$$B_{\text{QED}} \equiv m_e^2 c^3 / e \hbar \simeq 4.4 \times 10^{13} \text{ G}, \quad (4)$$

at which the electron cyclotron energy is equal to its rest mass. Some theories predict that under such a strong field, pair creation will become ineffective due to photon splitting, thus, suppressing the radio emission [3, 4].

Magnetars were historically identified as anomalous X-ray pulsars (AXPs) or soft gamma repeaters (SGRs) according to how they were first discovered. In contrast to RPPs, magnetars in an active state could have X-ray luminosities 1-2 orders of magnitude higher than  $\dot{E}$ . This requires an additional energy source other than rotation, which is generally believed to be the decay of their strong magnetic fields. The most remarkable feature of magnetars is their violent outbursts, during which the X-ray luminosity can increase by a few orders of magnitude. These are often accompanied with timing anomalies [e.g. 5, 6]. While radio pulsations have been detected from three magnetars [7, 8, 9], their radio emission is largely distinct from that of RPPs, including highly variable radio flux densities, and flat or inverted radio spectra [9, 10, 11, 12]. These suggest that they could have a different radio emission mechanism than that of the RPPs. For

<sup>2</sup> A catalog of magnetars can be found at <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>

the purpose of this review, we do not consider these radio-emitting magnetars as ‘radio pulsars’, and reserve the term for RPPs, even though some RPPs have no radio detection.

Thanks to the Parkes Multibeam Pulsar Survey (PMPS) [13, and references therein], over 700 new radio pulsars were discovered and a handful of them have spin parameters similar to those of the magnetars, implying comparable field strengths. Table 1 lists all known high-magnetic-field RPPs (hereafter, high- $B$  pulsars) with  $B > B_{\text{QED}}$ , together with a few other high- $B$  pulsars that have previously been studied. The objects are plotted in the  $P-\dot{P}$  diagram in Figure 1b, clearly indicating an overlapping parameter space with some magnetars. Therefore, high- $B$  pulsars present an important link between RPPs and magnetars and could help understand magnetar physics. In particular, one might expect high- $B$  pulsars to have higher X-ray luminosities than other radio pulsars, and possibly exhibit magnetar-like properties. We will describe some individual sources in the next section, and then discuss the connection of high- $B$  pulsars to other classes of neutron stars.

**TABLE 1.** Measured and derived properties of high- $B$  pulsars

Name*	$P$ (s)	$B$ ( $10^{13}$ G)	$\dot{E}$ (ergs s $^{-1}$ )	$\tau_c$ (kyr)	$d^{\dagger}$ (kpc)	$L_X^{**}$ (ergs s $^{-1}$ )	Ref.
J1847–0130	6.71	9.4	$1.7 \times 10^{32}$	83	8.4	$< 3.4 \times 10^{34}$	[14]
J1718–3718	3.38	7.4	$1.6 \times 10^{33}$	34	4.5	$0.14\text{--}2.6 \times 10^{33}$	[15]
J1814–1744	3.98	5.5	$4.7 \times 10^{32}$	85	10	$< 4.3 \times 10^{34}$	[16]
J1734–3333	1.17	5.2	$5.6 \times 10^{34}$	8.1	6.1	$0.1\text{--}3.4 \times 10^{33}$	[17]
J1819–1458 <sup>R</sup>	4.26	5.0	$2.9 \times 10^{32}$	117	3.6	$1.8\text{--}2.4 \times 10^{33}$	[18]
J1846–0258	0.33	4.9	$8.1 \times 10^{36}$	0.9	6.0	$2.5\text{--}2.8 \times 10^{34\dagger}$	[19]
						$1.2\text{--}1.7 \times 10^{35\ddagger}$	[19]
J1119–6127	0.41	4.1	$2.3 \times 10^{36}$	1.7	8.4	$1.9\text{--}3.5 \times 10^{33}$	[20]
J0847–4316 <sup>R</sup>	5.98	2.7	$2.2 \times 10^{31}$	790	3.4	$< 6 \times 10^{31}$	[21]
J1846–0257 <sup>R</sup>	4.48	2.7	$7.1 \times 10^{31}$	442	5.2	$< 1.8 \times 10^{32}$	[21]
B0154+61	2.35	2.1	$5.7 \times 10^{32}$	197	1.7	$< 1.4 \times 10^{31}$	[22]
B1916+14	1.18	1.6	$5.1 \times 10^{33}$	88	2.1	$1.1\text{--}2.3 \times 10^{31}$	[23]

\*\* converted into the 0.5–10 keV band.

† in 2000, prior to the 2006 outburst.

§ during the outburst in 2006.

\* the superscript <sup>R</sup> indicates that the pulsar is classified as a rotating radio transient (RRAT).

† estimated from the dispersion measure of the pulsars, except for PSRs J1846–0258 and J1119–6127, for which the distances are obtained from H I absorption measurements [24, 25].

## INDIVIDUAL HIGH- $B$ RPPS

In this section we describe details of some individual high- $B$ .

- **J1847–0130:** This 6.7s-period radio pulsar was discovered in the PMPS [14] and it has by far the highest known  $B$ -field among all RPPs in the ATNF Pulsar Catalog<sup>3</sup>. The spin-down-inferred  $B$ -field is  $9.4 \times 10^{13}$  G, well above the quantum

<sup>3</sup> <http://www.atnf.csiro.au/research/pulsar/psrcat/>

critical limit, and even higher than that of two magnetars, AXP 1E 2259+586 and SGR 0418+5729 [2]. This discovery demonstrates that the pulsar radio emission mechanism can work in such a strong field, presenting a challenge to some theories [e.g. 3]. The source is not detected in X-rays, however. A flux limit of  $5 \times 10^{33} \text{ ergs s}^{-1} \approx 10\dot{E}$  (2-10 keV) was obtained from *ASCA* observations and is not very constraining [14].

- **J1718–3718:** Also discovered in the PMPS [13], this is the second highest  $B$ -field RPP. An X-ray counterpart was found serendipitously in a *Chandra* exposure of a nearby source [15]. Deeper follow-up *Chandra* observations have detected pulsations in the soft X-ray band (0.8-2 keV) and better constrain the source spectrum [26]. However, the data indicate no evidence of long-term X-ray variability, although the pulsar exhibited a large glitch some time between 2006 August and 2009 January (Manchester & Hobbs, in preparation).
- **J1734–3333:** This pulsar has a strong  $B$ -field of  $5.2 \times 10^{13}$  G inferred from the spin-down, also exceeding the QED critical limit. Recently, Espinoza et al. [27] reported a braking index<sup>4</sup>  $n = 1.0 \pm 0.3$  using 12 years of phase-coherent radio timing data. This could imply a magnetic field that is growing with time, such that the trajectory on the  $P-\dot{P}$  diagram points toward the magnetar region. Therefore, the authors suggested that this radio pulsar may be a magnetar progenitor. Deep *XMM-Newton* observations have identified a faint X-ray counterpart, but found no sign of magnetar-like activity [17]. The X-ray luminosity in 0.5-2 keV is below  $0.1\dot{E}$ , similar to that of a typical RPP.
- **J1819–1458:** Three high- $B$  pulsars listed in Table 1 belong to the so-called “rotating radio transients” (RRATs) class of neutron stars, which are sporadic radio pulse emitters (see M. McLaughlin’s review in this Volume). There are nearly 50 known RRATs<sup>5</sup>, among which a handful have spin-down measurements that imply  $B$ -fields ranging from  $3 \times 10^{12}$  to  $5 \times 10^{13}$  G. Thus, not every RRAT is a high- $B$  pulsar and the connection between these two classes of neutron stars remains unclear. One particularly interesting object is RRAT J1819–1458, which was discovered in a search for isolated bursts in the PMPS data [28]. It has the highest  $B$ -field of  $5.0 \times 10^{13}$  G among all known RRATs [29]. X-ray observations with *XMM-Newton* found a possible spectral feature and indicate a high X-ray luminosity of the source, an order of magnitude larger than  $\dot{E}$  [18], suggesting that it is not entirely rotation-powered. On the other hand, deep *Chandra* observations reveal extended X-ray emission that could be an associated PWN [30], a feature commonly observed among energetic RPPs. Further studies are needed to identify the exact nature of this object.
- **J1846–0258:** Located at the center of supernova remnant Kes 75 (G29.7–0.3), this remarkable high- $B$  ( $4.9 \times 10^{13}$  G) pulsar is one of the youngest ( $\sim 900$  yr) known pulsar in our Galaxy. Although no radio emission is detected [31], it powers a bright PWN [19, 32] and spins down relatively steadily. This has allowed a braking

<sup>4</sup> The braking index is defined as  $n \equiv v\ddot{v}/\dot{v}^2$ , where  $v$ ,  $\dot{v}$  and  $\ddot{v}$  are the spin frequency, its time derivative and second derivative, respectively.

<sup>5</sup> <http://www.as.wvu.edu/~pulsar/rratalog/>

index measurement of  $n = 2.65 \pm 0.01$  [33]. Therefore, this object has long been considered as a RPP. Surprisingly, this pulsar exhibited magnetar-like bursts in 2006 May, with a substantial flux enhancement and spectral softening in X-rays [19, 34, 35]. Accompanied with this event was a sizable rotational glitch followed by unusually large recovery [36, 37]. Post-outburst observations reveal an apparent decrease in braking index of  $n = 2.16 \pm 0.13$  and larger timing noise than before, although the X-ray emission returned to its quiescent level months after outburst [38]. The spectacular outburst clearly indicates PSR J1846–0258 is a transition object between a RPP and a magnetar, raising the possibility that some high- $B$  pulsars could be quiescent magnetars, as first speculated by Kaspi and McLaughlin [15].

- **J1119–6127:** This young ( $\tau_c = 1.7$  kyr) and energetic ( $\dot{E} = 2.3 \times 10^{36}$  ergs s $^{-1}$ ) pulsar is associated with the supernova remnant G292.2–0.5 and has a strong  $B$ -field of  $4.1 \times 10^{13}$  G [39]. The recent detection of  $\gamma$ -ray pulsations with the *Fermi Gamma-ray Space Telescope* makes it the highest  $B$ -field  $\gamma$ -ray pulsar (P. den Hartog’s talk in this conference; Parent et al. in preparation). In X-rays, it is highly pulsed in the soft band (0.5–2 keV) with a pulsed fraction  $74\% \pm 14\%$ , suggesting intrinsic anisotropy of the thermal emission from the surface [20, 40]. With superb spatial resolution, *Chandra* observations led to the discovery of a faint PWN surrounding the pulsar [41], and helped to isolate the pulsar flux from the PWN. The pulsar spectrum consists of thermal and non-thermal components, and the former can be fitted by either a blackbody of temperature  $kT \sim 0.21$  keV or a neutron star atmosphere model with  $kT \sim 0.14$  keV [20, 40]. Hence, this object is the youngest RPP with thermal emission detected, and also one of the hottest. In the radio band, this pulsar exhibits different types of behavior and shows “RRAT-like” emission following glitches, possibly related to a reconfiguration of the magnetic field [42].

## THE CLASS OF HIGH- $B$ PULSARS

### Connection with Magnetars

As described above, most high- $B$  pulsars are very faint compared to their spin-down luminosities and show no magnetar behavior (except PSR J1846–0258), clearly distinct from active magnetars. Although based purely on their X-ray spectra, one cannot rule out the possibility that some of the high- $B$  pulsars could be quiescent magnetars, the three known radio-emitting magnetars show very different radio properties than RPPs, somewhat weakening this argument. This raises an important question: what is the intrinsic difference between these two classes of objects?

In Figure 1 high- $B$  pulsars and magnetars occupy an overlapping region in the  $P$ – $\dot{P}$  diagram, implying that the spin and spin-down rate are not sufficient parameters to determine the pulsar properties. One idea is that there could be some “hidden parameters” that differentiate the two populations, such as the neutron star mass [15] or the  $B$ -field configuration [14, 43]. In the latter picture, a magnetar field has additional quadrupole or higher multipole components, which have no effect on the spin-down torque. Another

attempt to unify these objects is by different orientations of the magnetic axes with respect to the rotation axes [44]. This model predicts an upper limit of  $2 \times 10^{14}$  G on the surface magnetic field of a radio pulsar.

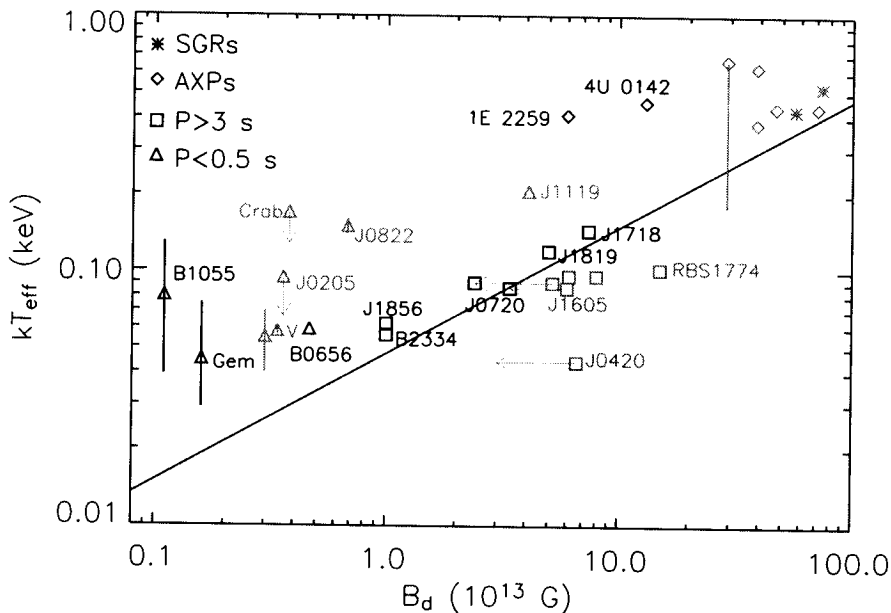
As an alternative, it is also possible that the  $B$ -field inferred from spin-down is not a reliable estimator of the true field strength due to extra spin-down torques. One plausible scenario is spin-down under the combined effects of magnetic braking and relativistic particle winds [45]. Depending on the wind luminosity, the latter term could be substantial, resulting in an overestimate of the surface field by an order of magnitude if Equation 3 is assumed. However, it has been argued that for magnetars, their wind flows may be episodic with small duty cycles, rendering the dipole spin-down approximation less biased [45]. Another source of spin-down could be propeller torque from a fallback accretion disk [46], such that a high- $B$  pulsar has a true surface field of only  $10^{12}$ - $10^{13}$  G, similar to those of other radio pulsars. However in this case, it is unclear if there would be radio emission from the pulsar, except under specific conditions [see 47].

## Connection with Other Radio Pulsars

Pons et al. [48] first noticed an apparent correlation between the effective temperature  $T_{\text{eff}}$  and surface  $B$ -field in a wide range of neutron stars, with  $T_{\text{eff}} \propto \sqrt{B}$  over three orders of magnitude (Figure 2). This has motivated a series of studies on the magneto-thermal evolution of neutron stars [48, 49, 50, 51]. In this model, the decay of the magnetic field provides crustal heating on the neutron star, which in turn affects the magnetic diffusivity and thermal conductivity [52, 53]. As a result, stars born with stronger magnetic fields ( $> 5 \times 10^{13}$  G) are expected to show significant field decay, which keeps them hotter for longer. While this model is capable of explaining the relatively high X-ray temperatures of magnetars compared with typical radio pulsars, we note that an updated plot using recent observations of high- $B$  pulsars shows a large scatter and the correlation seems weaker [23].

Another important parameter to consider is the pulsar age. Since the  $B$ -field and temperature likely decay at different rates, the plot above, which contains an ensemble of pulsars at different ages, could be biased. A comparison between the pulsar temperature and characteristic age indicates that high- $B$  pulsars appear to be systematically hotter than other radio pulsars (Figure 3), providing some support to the crustal heating model [23, 26, 49]. However, the data quality does not allow one to rule out the minimal cooling scenario. Thus, it remains unclear if  $B$ -field decay is a significant source of heating for high- $B$  pulsars [26].

Adding to the complication is that temperature measurements depend sensitively on the detailed physics of neutron star atmosphere, which is not fully understood. The X-ray luminosity, on the other hand, is less model-dependent, and it could offer a more robust comparison between different classes of objects. Figure 4 plots the X-ray luminosities against field strengths for the high- $B$  pulsars listed in Table 1, showing a hint of correlation [17]. However, many pulsars in the plot are not detected in X-rays or their luminosities are poorly constrained. Also, four out of five brightest objects are



Source: Pons et al. [48]

**FIGURE 2.** Effective temperatures versus  $B$ -fields for different classes of neutron stars, adopted from Pons et al. [48].

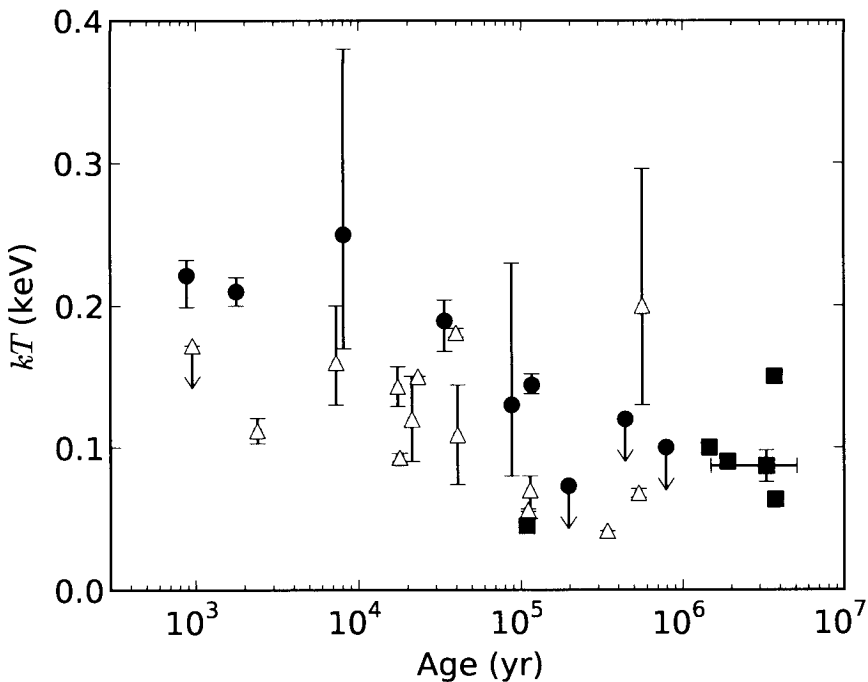
also the youngest, hence the possible trend may merely reflect luminosity evolution with time (except, interestingly, PSR J1819–1458 which has a relatively large characteristic age; see Table 1).

## FUTURE PROSPECTS

The case of PSR J1846–0258 has provided an important link between the classes of RPPs and magnetars. For further study, it is crucial to obtain more examples of transition objects. While detecting magnetar-like outbursts would give unambiguous evidence of such an object, it is observationally challenging because these events could be much less energetic than those in magnetars. In the absence of sensitive all-sky X-ray monitors, any timing anomaly may be a good indicator of a radiative event, as is often seen for magnetars. In practice, this would require regular radio timing observations with prompt X-ray follow-up after a glitch. Regular X-ray monitoring of high- $B$  pulsars is also useful for identifying long-term flux variability, which is another distinct feature of magnetars [e.g. 54].

Nearly half of the high- $B$  pulsars listed in Table 1 have only upper limits on their X-ray flux. Completing the sample will require deep X-ray observations, ideally with next-generation telescopes that have a large collecting area, such as the *International X-ray Observatory (IXO)*. This will give high quality spectra to pin down the surface





Source: Zhu et al. [26]

**FIGURE 3.** Blackbody temperatures versus ages for different neutron stars, adopted from Zhu et al. [26]. The circles, triangles and squares indicate high- $B$  pulsars, normal radio pulsars and thermal isolated neutron stars, respectively.

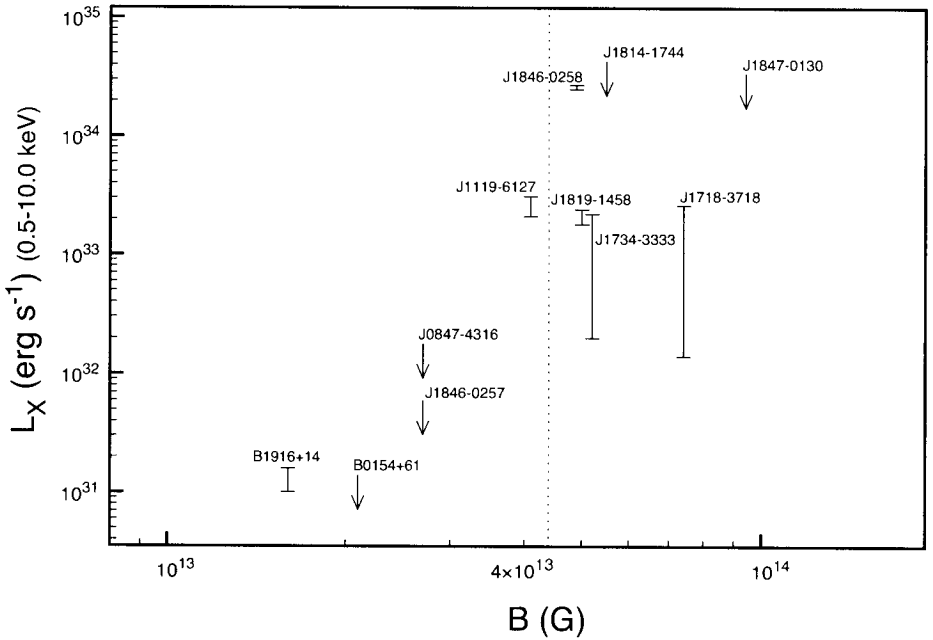
temperature of high- $B$  pulsars, and potentially reveal any spectral features that could provide direct measurements of the surface field strength.

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Source: Olausen et al. [17]

**FIGURE 4.** X-ray luminosities versus  $B$ -fields for high- $B$  pulsars, adopted from Olausen et al. [17].

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