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What is Special about HBRPs

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Abstract The Parkes Multibeam Survey led to the identification of a number of long-period radio pulsars with magnetic field well above the 'quantum critical field' of $\sim 4.4 \times 10^{13}$ G (HBRPs). Traditional pulsar emission theories postulate that radio emission is suppressed above this critical field. The aim of this project is to understand emission properties of HBRPs.

Key words: pulsars: general — stars: magnetic fields — radio continuum: stars

1 INTRODUCTION

About 1500 neutron stars have so far been detected in the Galaxy as radio pulsars, of which 125 are millisecond pulsars (from ATNF Pulsar Catalogue at http://www.atnf.csiro.au/research/pulsar/psrcat, see Manchester et al. 2005). The Parkes Multibeam Survey (hereafter PMS) doubled the number of known pulsars (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004; Faulkner et al. 2004). Prior to the PMS the highest measured neutron star surface magnetic field was 2.1×10^{13} G for the pulsar B0154+61. The PMS led to the identification of a number of 'HBRPs', radio pulsars with long periods and with surface magnetic fields near 10^{14} G (McLaughlin et al. 2004). Even more exotic neutron stars, with the surface fields clustered around $10^{14} - 10^{15}$ G, are the Anomalous X-ray Pulsars (AXPs) (Kaspi & Gavriil 2004) and Soft Gamma-rays Repeater (SGRs) (Kouveliotou 2003), now believed to be magnetars (Duncan & Thompson 1992). The fields of these sources, deduced from their dipole spin down rates ($B_{\rm surf} = 3.2 \times 10^{19} (P\dot{P})^{1/2}$), are well above the quantum critical magnetic field of $B_{\rm c} \sim 4.4 \times 10^{13}$ G. Existence of these long period radio pulsars with surface dipole magnetic field strengths higher than critical, demonstrates that radio emission can be produced in neutron stars with $B_{\rm surf} > B_{\rm c}$, despite the prediction of the radio-quiet boundary below which radio emission should cease (Baring & Harding 1998).

The HBRPs may be young objects that form a transition between normal radio pulsars and AXPs (McLaughlin et al. 2003). This suggests that there should be many more HBRPs than those currently known. It may be that the SGRs, AXPs and HBRPs form a continuum of magnetic activity, or they might be different phases/states of a more uniform class of object. In order to investigate these ideas we initiated a project with the main goal of understanding the emission properties of HBRPs. We chose a sample of 17 HBRPs, together with 17 low magnetic-field radio pulsars selected to have similar spin period distributions. We observed these 34 pulsars at three different frequencies in order to obtain their polarimetric characteristics as well as to find their flux densities and spectral indexes. High time resolution data on their individual pulses together with multi-frequency polarimetric data will provide us with a wealth of information about their emission process. We will compare observed characteristics of these two samples of pulsars using the Parkes radio telescope.

We organize this paper as follows. In section 2 we discuss super strong magnetic fields briefly, and then summarize the classes of pulsars. In Section 3 we present some preliminary results from our multi-frequency observations. In Section 4 we discuss the importance of understanding the emission properties from HBRPs and how they differ from normal pulsars. Our conclusion are given in the Section 5.

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2 NEUTRON STAR POPULATIONS

Neutron stars are strongly magnetized objects, with surface magnetic fields ranging from 10^6 G to 10^{15} G. The slowing down of pulsar rotation implies magnetic fields of order of 10^{11} G to 10^{15} G. The rapid rotation of such fields is important in generating relativistic particles and radio emission. Plasma accreting onto neutron stars in X-ray binary systems is channeled to the magnetic poles by fields ranging from 10^8 G to 10^{13} G.

2.1 Radio Emission in Super Strong Magnetic Fields

The condition that the cyclotron energy equal the rest energy of the electron corresponds to B equal to the quantum critical field strength of $B_\mathrm{c} = m_e^2 c^3/\hbar e = 4.4 \times 10^{13}$ G, and fields of this order or larger are said to be super strong. Most pulsars have $B_\mathrm{surf} \lesssim 0.1\, B_\mathrm{c}$, and HBRPs have $B_\mathrm{surf} \gtrsim B_\mathrm{c}$. Some other negligible or forbidden physical processes become important in pulsar magnetic fields, including birefringence of the vacuum, splitting of one photon into two, the decay of a single photon into an electron-positron pair, and the rapid radiative loss of perpendicular energy by all electrons, so that their motion is one-dimensional along the magnetic field lines.

The radio emission from pulsars is attributed to an electron-positron pair plasma created by one-photon decay into pairs. This is actually a four-stage process: a) a parallel electric field accelerates primary particles to extremely high energies, (b) these primaries emit gamma rays, initially directed nearly along the field lines, (c) as the photons propagate outward, the curvature of the magnetic field causes the angle between the photon and field line to increase, (d) when this angle is large enough, the photon decays into a pair. Any process that stops any of the steps (a)–(d) operating effectively can prevent copious pair production, so that the pulsar is 'dead' as a radio emitter. The death-line is usually attributed to the parallel electric field becoming too weak to provide effective primary particles. For $B_\mathrm{surf} > B_\mathrm{c}$ photon splitting can prevent (c) and (d) from operating effectively: a photon splits into two lower energy photons before it reaches the threshold for pair creation. Photon splitting is known to be possible only for photons of one polarization mode of the birefringent vacuum: photons with the other polarization mode are forbidden to split by selection rules attributed to Adler (1971). Baring and Harding (2001) speculated that this selection rule might not apply for $B_\mathrm{surf} > B_\mathrm{c}$, and that photons of both polarization might split, so that there is no pair creation for sufficiently high B, implying that neutron stars with $B_\mathrm{surf} \gtrsim 3 \times 10^{13}$ G should not be radio emitters. This prediction appears to be violated by the radio detection from two AXPs (Malofeev et al. 2005). It also suggest that HBRPs should not exist.

More recently, Weise and Melrose (2006) showed that Adler's selection rules continue to apply for $B_\mathrm{surf} > B_\mathrm{c}$. Hence photons in one mode do not experience photon splitting, but can decay into pairs. We conclude that the existence of HBRPs is consistent with theory.

2.2 Neutron Stars Classes

Based on observations, neutron stars may be classified as:

Radio active pulsars are traditional rotational-powered objects, divided into two main populations: *Millisecond pulsars*, with spin periods centered around $\sim 3\,\mathrm{ms}$ and magnetic fields around 10^8 G, with different evolutionary history from normal pulsars; and *Normal pulsars* with spin periods centered around $0.5\,\mathrm{s}$ and magnetic fields around $\sim 10^{12}$ G, thought to be born with short spin periods, to spin down on a time-scale of $10^5 - 10^6\,\mathrm{yrs}$, and to cease radio emission after around $10^7\,\mathrm{yrs}$); with distinguishable third class of *HBRPs*, which have similar spin parameters (long periods and high slowdown rates) as AXPs, but without detectable high-energy emission.

Radio-quiet isolated neutron stars: emit thermal-like X-rays, usually subdivided in four classes: *Anomalous X-ray pulsars*, a small class of solitary pulsars with spin periods in the $6 - 12\,\mathrm{s}$ range, very soft X-ray spectra, and strong magnetic fields of $10^{14} - 10^{15}$ G; *Soft Gamma-ray Repeaters*. emitting sporadic, intense flares of low-energy (soft) gamma rays, with periods and magnetic field in the similar range as AXPs; *Dim Thermal neutron stars*, which are not associated with supernovae remnants; and *Compact Central sources*, not identified with active radio pulsars or AXPs/SGRs, and with un-pulsed soft (thermal) emission. AXPs together with SGRs are believed to be *magnetars*, a class of neutron stars distinct from radio pulsars, in which magnetic energy, rather than the rotational energy, plays the dominant role in powering the X-ray and gamma-ray emissions.

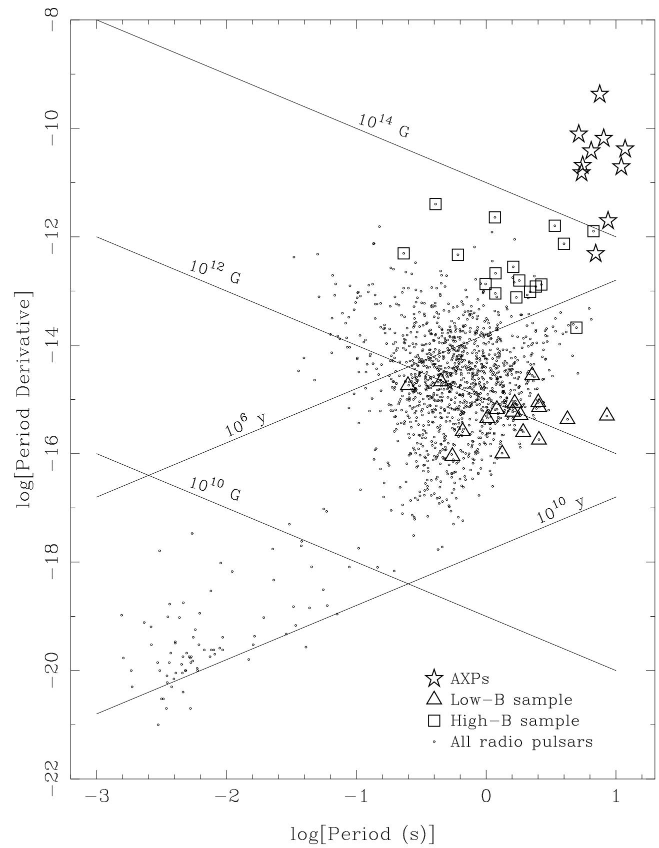

Fig. 1 A P–$\dot{P}$ diagram showing location of pulsars populations, as well as the location of pulsars from our samples. Dots correspond to all radio pulsars taken from the ATNF pulsar catalogue. Squares and triangles represent pulsars from our high-B and low-B samples, respectively. AXPs are marked with open stars. Lines of constant characteristic age and surface magnetic dipole field strength are shown.

Accretion-powered neutron stars are detected in X-ray binary systems (more than 200 known) as X-ray pulsars or X-ray bursts powered by thermonuclear flashes.

3 SOME PRELIMINARY RESULTS

3.1 Observed Samples

The location of our sample pulsars on the $P - \dot{P}$ diagram is shown in Figure 1. Seventeen HBRPs ($B_{\rm surf} > 10^{13}$ G) are marked with squares. The low-B pulsars sample ($B_{\rm surf} \leq 10^{12}$ G), which has a similar period distribution to the high-B sample, appear as 17 triangles. Observations were carried out using the Parkes 64-m radio telescope, in two sessions, 2005 May 23 – 25, and 2005 December 02 – 05. The 20-cm observations were made using the central beam of the Parkes multibeam receiver with central frequencies of 1433 MHz and 1369 MHz. The 10-cm and 50-cm observations were made using the the dual frequency $10/50\,\rm cm$ receiver with a central frequencies at 3100 MHz and 685 MHz. The most exotic pulsars discovered by PMS are J1718–3718, J1734–3333, J1814–1444, and J1847–0130, with $B_{\rm surf} \gtrsim B_{\rm c}$, specifically, 7.4×10^{13} G, 5.2×10^{13} G, 5.5×10^{13} G and 9.4×10^{13} G, respectively.

3.2 PSR J1734–3333

We show preliminary results for pulsar J1734–3333 at two different frequencies. This pulsar is young, $\sim 8000\,\rm yrs$ old, with $P = 1.17\,\rm s$ and $B_{\rm surf} > B_{\rm c}$. Figure 2 shows the polarization profiles at $20\,\rm cm$ and $10\,\rm cm$. The 10 cm profile shows two main components; the dominant trailing component has strong circular polarization. Linear polarization is significant for both components with a position-angle swing of opposite sign through the two components. The 20 cm profile clearly shows the effects of ray scattering by irregularities in the ISM, broadening an intrinsically sharp pulse. More distant pulsars with higher DMs are more likely to be strongly scattered; PSR J1734–3333 has $\mathrm{DM} = 578\,\mathrm{cm}^{-3}\,\mathrm{pc}$ and distance of $d = 7.40\,\mathrm{kpc}$.

The only publicly available data for this pulsar are filterbank data at 1374 MHz from the discovery paper (Morris et al. 2002). More than 80% of all our observed 34 pulsars have published data only from their discovery at 20 cm. Detailed results on multi-frequency observations of HBRPs will be published in the near future.

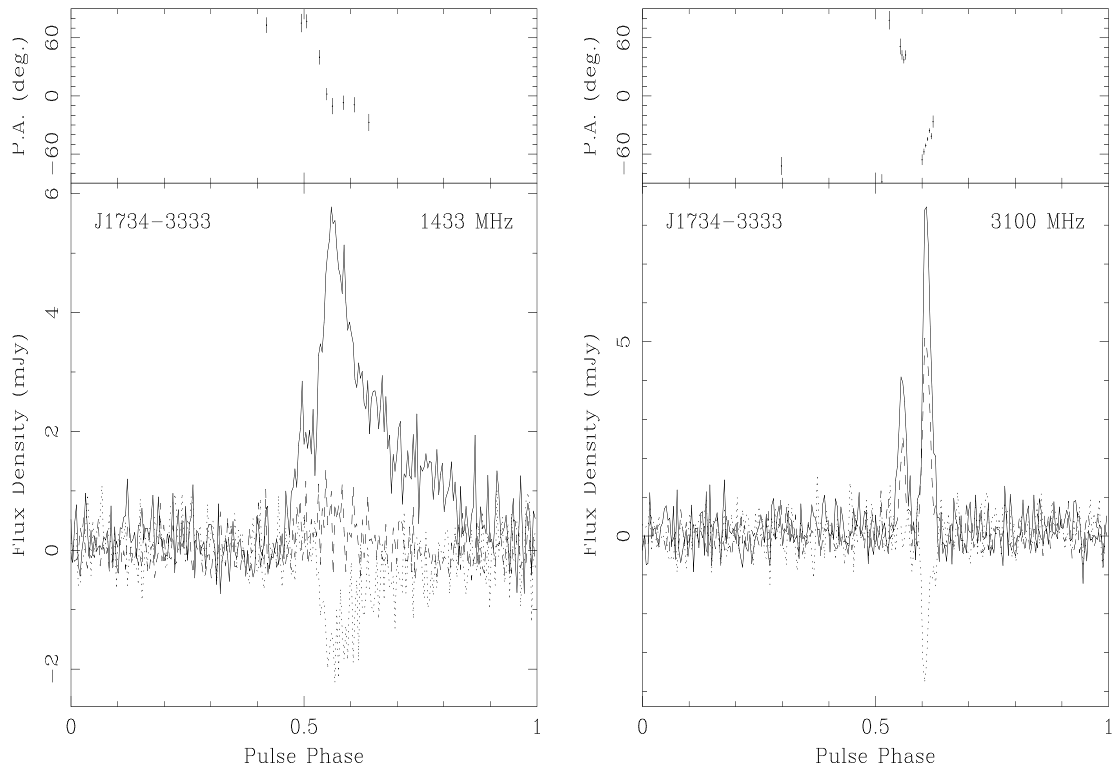

Fig. 2 Polarization profiles for PSR J1734–3333 at 20 cm and 10 cm, showing 360° of rotational phase, with total intensity as a solid line, linearly polarized intensity as a dashed line and circularly polarized intensity as a dotted line. The upper panel shows the position angle of the linear polarization.

4 DISCUSSION

The motivation for this project arose from the desire to understand recent results of pulsar population analysis (Vranesevic et al. 2004) which show that pulsars with high magnetic fields contribute almost half to the total pulsar birthrate, despite the fact that such high field pulsars are restricted to only few per cent of the total pulsar population. Furthermore, in the same paper, it was shown that up to 40% of all pulsars are born with periods in the range $100 - 500\,\mathrm{ms}$, which is in contradiction to the canonical view that all pulsars are born as fast rotators ($P_0 \leq 100\,\mathrm{ms}$). Kaspi and McLaughlin (2005) pointed out the overlap area (below 10^{14} G), where a couple of magnetars have fields and periods that are comparable to those of HBRPs. This overlap suggests that there could exist lower field magnetars (with $B_{\mathrm{surf}} < 10^{14}\,\mathrm{G}$) that will evolve into X-ray silent HBRPs (Ferrario and Wickramasinghe 2006). The same authors have indicated possibility of discovery of 'hybrid' young objects having these high magnetic fields, exhibiting both magnetar and radio pulsar characteristics.

5 CONCLUSIONS

Although HBRPs and magnetars have similar spin parameters, their emission properties are different. It has been suggested that pulsars-like objects could evolve from normal radio pulsars to magnetars (Lyne 2004; Lin & Zhang 2004). Ferrario and Wickramasinghe (2003, 2006) argued that the initial neutron stars spin periods may depend critically on their magnetic fields, in particular, there is a tendency for high field systems to be born as slow rotators. These suggestions may reveal a missing link between radio pulsars and magnetars.

We hope to provide solid constraints on HBRP's radio emission characteristics by comparing HBRPs properties with the properties of normal pulsar population using their multi-frequency and high time resolution data.

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