Part 3
Studies of Radio Emission

Section B. Averaged Pulses

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Ha, ha, ha, ha, staying alive, staying alive: A radio pulsar with an 8.5-s period challenges emission models.

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Abstract. We report the discovery of the longest known radio pulsar period. PSR J2144–3933, previously thought to have a period of 2.84 s, actually has a period of 8.51 s. Under the usual assumptions about the stellar equation of state, this pulsar has an average surface dipolar magnetic field strength of $\sim 2.0 \times 10^{12}$G. According to popular theories of the emission mechanism this pulsar should not be emitting radio waves because its long period and magnetic field strength make pair creation impossible for all reasonable magnetic field configurations. Either assumptions about the equation of state are incorrect, or the emission theories must be revised.

1. Introduction

Copious electron-positron pair creation in gaps above the polar caps of radio pulsars has long been widely accepted as essential to the pulsar radio emission process (Sturrock 1971; Ruderman & Sutherland 1975; Machabeli & Usov 1979; Cheng & Ruderman 1980; Beskin, Gurevich, & Istomin 1988). In such models, the pairs are created from the interaction of γ-photons with the polar magnetic field: $\gamma + \mathbf{B} \rightarrow \mathbf{e}^{+} + \mathbf{e}^{-} + \mathbf{B}$. The γ-rays must be sufficiently energetic to create pairs. Since the maximum energy of the γ-rays depends on the accelerating electric potential difference across the gap, and since this in turn is inversely related to the pulsar period, copious pair-creation, and hence radio emission, should cease when the period exceeds a threshold.

The value of the threshold depends on the surface magnetic field strength and configuration because these determine the mean free path length of a γ-photon. For a given magnetic field configuration, the locus of P–B_s values at which radio emission ceases defines a 'death-line' in the P–B_s diagram, where B_s is the surface dipole magnetic field strength. In figure 1, death-line A corre-

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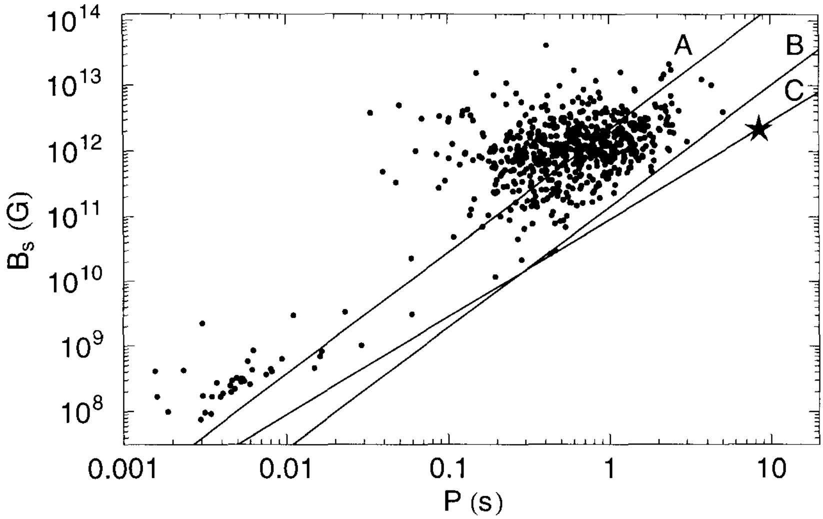

Figure 1. Distribution of known pulsars (excluding globular cluster pulsars) on the $P - B_s$ plane. PSR J2144−3933 is marked with a $\star$. The sloping lines are 'death lines' (see text); A: $4 \log B_s - 7.5 \log P = 49.3$, B: $7 \log B_s - 13 \log P = 78$ and C: $4 \log B_s - 6 \log P = 43.8$.

sponds to the curvature of a centred dipolar magnetic field, death-line B to the largest reasonable curvature and death-line C is an extreme and unlikely case (Chen & Ruderman 1993). Pulsars to the right of line C should not produce radio emission.

2. Observations and Analyses

PSR J2144−3933 was discovered during the Parkes Southern pulsar survey (Manchester et al. 1996; Lyne et al. 1998) in which automated software determined its period to be 2.84 s. Further observations and analyses of this pulsar, including the derivation of a timing solution (D'Amico et al. 1998), assumed this to be the correct period.

As part of an investigation of pulse scintillation (Johnston, Nicastro, & Koribalski 1998), the pulsar was observed for approximately 45 min in October 1994. The observations were conducted at 436 MHz using the Parkes radio telescope in a continuous sampling mode. The dual-channel cooled receiver had a bandwidth of 32 MHz. The effects of interstellar dispersion were removed using a 256-channel filterbank across the band and the sample interval was 1.2 ms.

Our analysis of pulse-to-pulse intensity fluctuations in these data revealed that significant pulsed emission was only evident every third pulse, or multiples there-of. The simple interpretation of this result is that the true period is three times the nominal value, or 8.51 s. Folding the data at this period gives a narrow, approximately Gaussian mean pulse profile with a complete absence of pulsed emission at the one- and two-thirds points—consistent with the identification of

8.51 s as the true period (Young, Manchester, & Johnston 1999). This rotation period is by far the longest of any known radio pulsar. The previous longest (Camilo & Nice 1995) was PSR J1951+1123 with a period of 5.09 s.

With a half-power width of $0^\circ.84$ of longitude, the pulse profile is the narrowest known. It implies a similarly narrow emission beam which is consistent with the known inverse relationship between pulse period and beamwidth (Lyne & Manchester 1988; Rankin 1990). Polarization observations (Manchester, Han, & Qiao, 1998) strongly suggest that the emission is of 'core' type (Rankin 1983; Lyne & Manchester 1988) from the region of a magnetic polar cap with the beam direction close to that of the magnetic axis. Rankin's (1990) empirical relation for the pulse width of core emission at a frequency of 1 GHz predicts a width of $0^\circ.84$ for a perpendicular rotator with a pure centred dipole magnetic field. This is in good agreement with the width at 1 GHz of about $0^\circ.82$, inferred from measurements at 436 and 659 MHz, and provides further support to the identification of the pulse as core emission.

We have conducted a re-analysis of the 1993 – 1997 timing data along with more recent data up to August 1998. The updated timing parameters are published in Young et al.. B_s is estimated to be 2.0×10^{12} G.

3. Discussion

PSR J2144−3933 lies to the right of death-line C in figure 1. It is the first pulsar known to do so and calls into question the assumptions made in deriving the death-lines.

One possibility is that the neutron star properties differ from those usually assumed. The estimated value of B_s is proportional to $(I/R^6)^{1/2}$, where I and R are the neutron-star moment of inertia and radius respectively (Manchester & Taylor 1977). For different equations of state, $(I/R^6)^{1/2}$ may vary by up to an order of magnitude. If PSR J2144−3933 has a larger-than-average value of $(I/R^6)^{1/2}$, the magnetic dipole field strength may be large enough to permit pair creation and hence radio emission. However, a factor of 60 increase of $(I/R^6)^{1/2}$ would be required to place the pulsar on death-line A corresponding to the centred dipolar magnetic field suggested by Rankin's (1990) model.

Alternatively, Arons (1998; this vol.) argues that frame-dragging, strongly off-set dipolar magnetic fields and a particular cooling physics, delays pulsar death to sufficiently large periods.

Otherwise, it may be that the radio emission process does not depend on pair creation. Weatherall & Eilek (1997) have suggested that pulsars below line A all have conal properties and that conal emission may be generated by a mechanism not dependent on pair creation. PSR J2144−3933 has core-type signatures, and is beyond death line A. We suggest that the fact that few core-dominated pulsars are seen beyond death line A is just a selection effect due to the narrow beamwidth of core emission.

Perhaps PSR J2144−3933 is the only one of its kind. However, a more reasonable explanation for its exalted position in the pulsar data base is that we simply have not yet been able to detect other similar pulsars. PSR J2144−3933 has the smallest spin-down luminosity ($\sim 3 \times 10^{28}$ erg s^{-1}) of any known pulsar. From its dispersion measure (D'Amico et al. 1998; Taylor & Cordes 1993), its distance is estimated to be only about 180 pc. Hence its radio luminosity, $L_{400} \sim 0.13$ mJy kpc^2, is low, and assuming a circular beam, the beaming fraction is also very small, ~ 0.01. These factors together imply that we could detect only a very small proportion of the total population of such objects in the Galaxy. While extrapolation from the detection of a single object has an unknowable uncertainty, this detection implies a Galactic population of similar pulsars of order 10^5, comparable to previous estimates of the size of the total pulsar population (Lyne, Manchester, & Taylor 1985; Lorimer et al. 1993).

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