

Modelling of isolated radio pulsars and magnetars on the fossil field hypothesis

Lilia Ferrario[★] and Dayal Wickramasinghe

Department of Mathematics, The Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

We explore the hypothesis that the magnetic fields of neutron stars are of fossil origin. For parametrized models of the distribution of magnetic flux on the main sequence and of the birth spin period of the neutron stars, we calculate the expected properties of isolated radio pulsars in the Galaxy using as our starting point the initial mass function and star formation rate as a function of Galactocentric radius. We then use the 1374-MHz Parkes Multi-Beam Survey of isolated radio pulsars to constrain the parameters in our model and to deduce the required distribution of magnetic fields on the main sequence. We find agreement with observations for a model with a star formation rate that corresponds to a supernova rate of 2 per century in the Galaxy from stars with masses in the range 8–45 M_{\odot} and predict 447 000 active pulsars in the Galaxy with luminosities greater than 0.19 mJy kpc². The progenitor OB stars have a field distribution which peaks at ~ 46 G with ~ 8 per cent of stars having fields in excess of 1000 G. The higher-field progenitors yield a population of 24 neutron stars with fields in excess of 10^{14} G, periods ranging from 5 to 12 s, and ages of up to 100 000 yr, which we identify as the dominant component of the magnetars. We also predict that high-field neutron stars ($\log B > 13.5$) originate preferentially from higher-mass progenitors and have a mean mass of $1.6 M_{\odot}$, which is significantly above the mean mass of $1.4 M_{\odot}$ calculated for the overall population of radio pulsars.

Key words: stars: early-type – stars: magnetic fields – stars: neutron – pulsars: general.

1 INTRODUCTION

A striking feature of the white dwarfs and the neutron stars is the wide range of magnetic field strengths seen in each of these groups. In isolated magnetic white dwarfs (about 15 per cent of the total white dwarf population), the field strengths are measured directly through the Zeeman effect and range from $\sim 10^5$ to 10^9 G. In isolated radio pulsars, the field estimates are in the range $\sim 10^{11}$ – 10^{14} G and are based on the measured spin down rates and the assumption of dipole radiation. Observations in the X- and γ -ray spectral regions have revealed the presence of a class of neutron stars with higher inferred fields, namely, the anomalous X-ray pulsars (AXPs) and the soft gamma repeaters (SGRs). These neutron stars are often referred to as ‘magnetars’ and have estimated field strengths in the range $\sim 10^{14}$ – 10^{15} G.

Possible explanations for the magnetic fields in neutron stars are that the fields are either (i) essentially of fossil origin (e.g. Ruderman 1972) or (ii) generated by a convective dynamo (Thompson & Duncan 1993). At the present time, this issue remains unresolved (see Mestel 2003, for a comprehensive review).

In the case of the white dwarfs, a direct link can be made between magnetism in the compact star phase and the main sequence via the well-documented properties of the chemically peculiar Ap and Bp stars (Wickramasinghe & Ferrario 2005) and has been a major factor supporting (i) for the white dwarfs.

Magnetism is not as well documented in the more massive ($\gtrsim 8 M_{\odot}$) upper main-sequence stars that evolve into neutron stars. The only known stars with a directly measured magnetic field are θ Orion C, with a dipolar magnetic field $B_p = 1100$ G (Donati et al. 2002), and HD191612 with a field of $B_p = 1500$ G (Donati et al. 2006). Their mass is estimated around $40 M_{\odot}$, with the latter star slightly more evolved than the former. Interestingly, the magnetic fluxes of both these stars (1.1×10^{27} G cm² for θ Orion C and 7.5×10^{27} G cm² for HD191612) are comparable to the flux of the highest-field magnetar SGR 1806–20 (5.7×10^{27} G cm²). There is also indirect evidence from studies of stellar winds from massive stars that magnetism may be widespread among OB stars (e.g. Wade 2001). These facts, taken together with the scaling that exists between the dipolar field strengths of the white dwarfs and the neutron stars (Fig. 1), suggest that a prima facie case can be made for a fossil origin of fields also in the neutron stars. The fossil field hypothesis provides a natural explanation for the wide range of observed magnetic field strengths in a given class as being the

[★]E-mail: lilia@maths.anu.edu.au

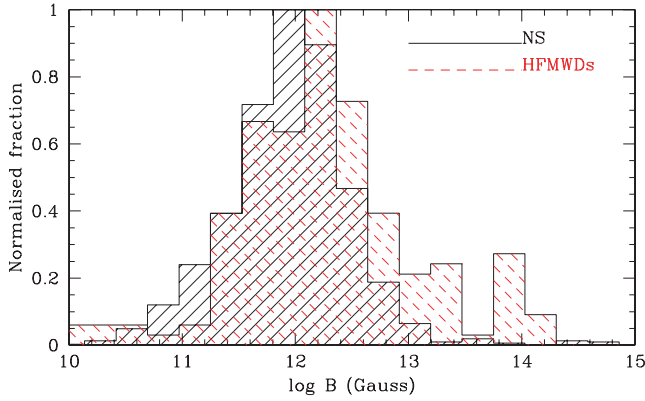


Figure 1. Black histogram (solid line): field distribution of neutron stars. Red histogram (dashed line): field distribution of high-field magnetic white dwarfs when their radii are shrunk to that of a typical neutron star radius of $\sim 10^6$ cm. This figure is in colour in the online version of the article.

result of inhomogeneities in the interstellar magnetic field strength in star-forming regions.

Calculations of pre-main-sequence evolution have shown that stars more massive than $\sim 2 M_{\odot}$ are likely to begin their main-sequence phase with a primordial magnetic flux entrapped in radiative regions supporting the fossil hypothesis (Tout, Livio & Bonnell 1999; Moss 2003). There are no detailed studies on the interplay between fossil fields and subsequent stellar evolution. This problem has been discussed by Tout, Wickramasinghe & Ferrario (2004, hereafter TWF). They argued that provided there are regions of the star that are radiative during subsequent evolution, a fossil main-sequence poloidal magnetic flux could survive through to the compact star phase.

In this paper, we investigate the consequences of the fossil field hypothesis for the origin of magnetic fields in neutron stars by carrying out population-synthesis calculations for different assumptions on the distribution of the magnetic flux of massive ($\gtrsim 8 M_{\odot}$) main-sequence stars and of the field dependence of the initial birth period of neutron stars. We model the observed properties of the population of isolated radio pulsars in the 1374-MHz Parkes Multi-Beam Survey (PMBS, Hobbs et al. 2004; Kramer et al. 2003; Morris et al. 2002; Manchester et al. 2001) to constrain our model parameters, and use these to deduce the required magnetic properties of the progenitor OB stars.

2 THE MODEL

2.1 The progenitors

We assume that neutron stars are formed in the Galactic disc from stars with $8 \leq M/M_{\odot} \leq 45$ and that black holes form from larger-mass stars. The situation is not as clear cut, from a theoretical point of view, because of the uncertainties in estimating the effects of fall-back (e.g. Heger et al. 2003). None the less, there is now overwhelming observational evidence that progenitors of neutron stars could be as massive as $40\text{--}50 M_{\odot}$ (e.g. Gaensler et al. 2005; Muno et al. 2006).

We assume an initial mass function $\psi(M_i)$ with a power-law index $\alpha_3 = 2.7$ (Kroupa 2002), and a constant star formation rate $S(r_g)$ at a given Galactocentric radius r_g . The radial dependence of $S(r_g)$ is obtained from the data presented by Boissier et al. (2003). The stars are distributed perpendicularly to the Galactic plane (the z -direction)

exponentially using the scaleheights as a function of initial mass given by Rana (1987) supplemented at the high-mass end by the observed Wolf–Rayet distribution of Conti & Vacca (1990). These values range from a scaleheight of 100 pc for a $8.4 M_{\odot}$ star to 45 pc for a $45 M_{\odot}$ star, which is in agreement with the more recent results of Reed (2000).

Unlike in the case of the white dwarfs, for the neutron stars the initial (M_i) to final mass (M_{NS}) relationship is not well constrained by observations. Masses are known for a handful of neutron stars, particularly in binaries, and these are observed to cluster around $M_{\text{NS}} \sim 1.4 M_{\odot}$, close to the core collapse mass for an initial mass $M_i \sim 8 M_{\odot}$. In our calculations, we use the relationship obtained by Heger, Woosley & Spruit (2005).

In the simple model of TWF, a star of mass M_i that collapses from the interstellar medium entraps a magnetic flux that is proportional to the ambient interstellar (primordial) magnetic field B_{ISM} and the square of its initial radius R_i . If we assume an initially nearly uniform density, it follows that the magnetic flux $\Phi \propto B_{\text{ISM}} M_i^{2/3}$. The variations expected in the interstellar magnetic field will then determine the distribution of magnetic fluxes in the progenitor stars. We parametrize the magnetic flux distribution $\chi(\Phi)$ by assuming that all massive stars are magnetic, and that the magnetic flux Φ is given as the sum of two Gaussians in the logarithm with dispersions $\sigma_{\log \Phi 1}$ and $\sigma_{\log \Phi 2}$ with appropriate weightings. The mean values are assumed to have the form

$$\langle \log \Phi \rangle = \log(\Phi_m) + \frac{2}{3} \log \left(\frac{M_i}{9 M_{\odot}} \right), \quad (1)$$

where the subscript m takes the values 1 and 2 for the two Gaussians. The magnetic fluxes are in units of G cm^2 .

2.2 Parametrization of the birth properties of the neutron stars

With the prescription of Section 2.1, we generate neutron stars with a range of masses. Our assumption that the magnetic flux is conserved during post-main-sequence evolution to the compact star phase allows us to calculate the birth surface magnetic fields of these neutron stars from:

$$B_{\text{NS}} = \frac{\Phi}{\pi(R_{\text{NS}})^2} \text{ G}, \quad (2)$$

where R_{NS} is the radius of the neutron star in cm given by the mass–radius relationship for neutron stars which depends on the equation of state. We adopt the values obtained with the unified Skyrme Lyon (SLy) equation of state of Douchin & Haensel (2001).

We follow the motions of these stars by integrating the equations of motion in the Galactic potential of Kuijken & Gilmore (1989), assuming that they are born with a kick velocity that is independent of the progenitor mass and is given by a Gaussian distribution (e.g. Hobbs et al. 2005) with velocity dispersion σ_v .

Radio pulsars are generally observed not to have a braking index of 3 (e.g. Cordes & Chernoff 1998). However, to minimize the number of free parameters, we assume, in common with many other theoretical studies, that the spin down of radio pulsars is by dipole radiation:

$$\dot{P} = 9.76 \times 10^{-16} \left(\frac{R_{\text{NS}}}{10^6 \text{ cm}} \right)^6 \left(\frac{10^{45} \text{ g cm}^2}{I} \right) \left(\frac{B_{\text{NS}}}{10^{12} \text{ G}} \right)^2 \left(\frac{s}{P} \right) \text{ s s}^{-1}, \quad (3)$$

where I is the moment of inertia as derived by Douchin & Haensel (2001) and P is the period in seconds. We have explicitly assumed

that the time-scale for field decay is longer than the ages of the pulsars, although the issue of whether field decay is necessary to explain their detailed properties remains an open question (e.g. Gonthier et al. 2002).

We may expect the birth period of the compact star to be determined by the magnetic flux of the progenitor star and its initial angular momentum (e.g. Brecher & Chamugam 1983; Narayan 1987). The complex interactions that occur between magnetic fields and rotation during stellar evolution and the mechanisms responsible for the transport of angular momentum are still poorly understood (e.g. Spruit & Phinney 1998; Watts & Andersson 2002; Fryer & Warren 2004; Heger et al. 2005; Ott et al. 2005). Magnetic fields must play a role in transporting angular momentum outwards from the stellar core to the stellar envelope because otherwise all compact stars would be born at break-up velocity, which is not the case (e.g. Migliazzo et al. 2002; Kramer et al. 2003). Heger et al. (2005) have considered this problem, but only in the weak field regime not directly relevant to the fossil field hypothesis. They report that the rotation periods they find are generally too small to explain pulsar observations. On the other hand, Ott et al. (2005) have proposed that a propeller mechanism operating on fall-back material may slow down the rotation of pulsars at birth. Interestingly, we know that there is strong direct evidence for higher-field objects to be slower rotators in the magnetic white dwarfs and we speculate that this may be a general characteristic of stars with magnetic fields of fossil origin (see Ferrario & Wickramasinghe 2005, for scaling of rotation properties) and thus allow for this possibility in our modelling.

We model the birth spin periods of neutron stars $P_0(B_{\text{NS}})$ by assuming they are distributed as a Gaussian $\pi(P_0)$ with a dispersion σ_{P_0} about a mean $P_0(B_{\text{NS}})$ which depends linearly on the magnetic field

$$\langle P_0(B_{\text{NS}}) \rangle = \left(\frac{P_a}{s} \right) + \alpha \left(\frac{B_{\text{NS}}}{10^{12} \text{ G}} \right) \text{ s}. \quad (4)$$

This is clearly a first approximation (e.g. in fall-back models, a field dependence $\propto B_{\text{NS}}^{6/7}$ may be more appropriate). For different assumed values of $\alpha \geq 0$, we constrain the parameters P_a and σ_{P_0} by fitting the observations of isolated radio pulsars in the PMBS taken from the Australia Telescope National Facility (ATNF) catalogue (Manchester et al. 2005).

To fit these observations, we also have to model the radio luminosity. Guided by the expected power-law dependence on P and \dot{P} , and following previous investigators, we have assumed that the luminosity L_{400} at 400 MHz can be described by a mean luminosity of the form

$$\log \langle L_{400} \rangle = \frac{1}{3} \log \left(\frac{\dot{P}}{P^3} \right) + \log L_0 \quad (5)$$

with $\log L_0 = 7.2$. Here the luminosities are in units of mJy kpc². We have modelled the spread around L_{400} using the dithering function of Narayan & Ostriker (1990):

$$\rho_L(\lambda) = 0.5\lambda^2 \exp(-\lambda) \quad (\lambda \geq 0), \quad (6)$$

where

$$\lambda = b \left(\log \frac{L_{400}}{\langle L_{400} \rangle} + a \right) \quad (7)$$

and a and b are constants to be determined (Hartman et al. 1997). The luminosity at 400 MHz is then scaled to the observed PMBS frequency of 1374 MHz using a spectral index of -1.7 (Gonthier et al. 2002).

In our studies, we have adopted the radio death line predicted for a multipolar field configuration near the stellar surface in a space-charge-limited flow model (Zhang, Harding & Muslimov 2000), that is,

$$\log \left(\frac{\dot{P}}{s \text{ s}^{-1}} \right) = 2 \log \left(\frac{P}{s} \right) - 16.52. \quad (8)$$

2.3 The calculation of population characteristics

We calculate the total number of neutron stars in the Galaxy with period up to P by evaluating the integral

$$N(\leq P) = \int_0^{2\pi} \int_0^{15} \int_{P_{01}}^{P_{02}} \int_{P_0}^P \int_{\Phi_{\min}}^{\Phi_{\max}} \int_8^{r_{45}} \psi(M_i) \chi(M_i, \Phi) \pi(P_0) r_g S(r_g) \times dM_i d\Phi \frac{dP}{P} dP_0 dr_g d\phi. \quad (9)$$

Here, r_g (in kpc) is the Galactocentric radial coordinate, and ϕ is the Galactic longitude. \dot{P} is calculated from equation (3) in appropriate units using the magnetic field $B_{\text{NS}}(\Phi(M_i))$ derived from equation (2). The limits P_{01} , P_{02} , Φ_{\min} and Φ_{\max} are chosen to adequately sample the Gaussian distributions.

To compare our theoretical calculations with the PMBS isolated pulsars, we need to know the current location of each star that can contribute to the integral. To achieve this, we distribute the stars in velocity space according to the prescription of Section 2.2 with $\sigma_v = 380 \text{ km s}^{-1}$ and in the z -direction according to the masses of their progenitors as detailed in Section 2.1. Their spatial location at the current epoch is then determined by solving the equations of motion in the Galactic potential. The dispersion and scattering measures DM and SM of the pulsars are calculated using the FORTRAN program of Cordes & Lazio (2002). Finally, the pulsar luminosities are assigned according to equations (5)–(7).

Once all the intrinsic properties of our model pulsars are determined, these are fed through a filtering program kindly provided to us by Natasa Vranesovic (private communication) that checks the pulsars for detectability by the PMBS.

Finally, since the radio emission of pulsars is anisotropic, we use the Tauris & Manchester (1998) beaming model to obtain the correct fraction of detected pulsars:

$$f(P) = 0.09 \left[\log \left(\frac{P}{s} \right) - 1 \right]^2 + 0.03. \quad (10)$$

3 RESULTS AND DISCUSSION

Our approach has been to focus on constraining the key parameters that we have introduced for describing the magnetic flux distribution on the main sequence and the distribution of the initial birth period assuming that the remaining parameters of the model are within the ranges given by previous investigators. We have used as our basic observational constraints the 1D projections of the data comprising the number distributions in period P , magnetic field B_{NS} , period derivative \dot{P} and radio luminosity L_{1374} , noting that these distributions are not all independent.

The best-fitting model to the observations of the PMBS pulsars was determined ‘by eye’ after conducting hundreds of trials. We have found this method more reliable than the standard Kolmogorov–Smirnov (K–S) statistic. Our results are shown in Fig. 2.

The initial period distribution is described by $P_a = 0.22 \text{ s}$, $\sigma_{P_0} = P_0/2$ and $\alpha = 0.01$. The magnetic flux distribution is described

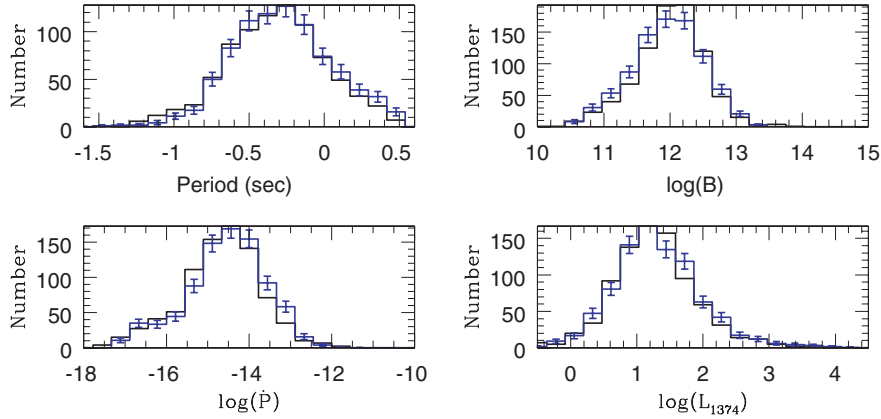


Figure 2. Our model (blue) overlapped with the PMBS data of the isolated radio pulsars from the ATNF catalogue (<http://www.atnf.csiro.au/research/pulsar/pulscat>). The errors are given by \sqrt{N} , where N is the number of objects in each bin. This figure is in colour in the online version of the article.

by two Gaussians of means and spreads $\log \Phi_1 = 26.2$, $\sigma_{\log \Phi_1} = 1.0$, and $\log \Phi_2 = 25.2$, $\sigma_{\log \Phi_2} = 0.61$, respectively, weighted in the ratio 1:5. The parameters for the luminosity model are $a = 1.8$ and $b = 2.8$.

This model reproduces the observed total number of pulsars in the PMBS, once we exclude the millisecond pulsars ($P < 20$ ms). The star formation rate is normalized to $2.5 M_{\odot} \text{pc}^{-2} \text{Gyr}^{-1}$ at the Galactocentric radius of the Sun, which is within the uncertainty in the Boissier et al. (2003) relationship. This corresponds to a Galactic supernova rate of 2 per century.

In a broad sense, the distribution that we use for the magnetic flux has the strongest influence on the location of the peak in the magnetic field distribution of the pulsars, while the mean period P_a and the width of the period distribution σ_{P_0} have a strong influence on the period distribution, although clearly, period and field distributions are interlinked through period evolution which depends on the magnetic field. We find that we cannot model both the field distribution and the period distribution at the same time if we assume that all pulsars are born at a period less than 50 ms. Such models give an excess of stars at low periods which is not consistent with the results of Vranesevic et al. (2004) who find that up to 40 per cent of pulsars are born with periods in the range 0.1–0.5 s. Regimbau & de Freitas Pacheco (2001) also noted that most pulsars are born with $P > 0.1$ s and conduct their population-synthesis studies using a Gaussian with a mean birth period $P_0 = 0.29$ s and a spread of 0.1 s, while Faucher-Giguère & Kaspi (2005) used a Gaussian with a mean birth period $P_0 = 0.3$ s and a spread of 0.15 s. All these results contradict the view that all pulsars are born as fast rotators ($P_0 \leq 0.1$ s) which arises from observational selection effects, since young and fast neutron stars (e.g. the Crab pulsar) would be more easily detectable as radio pulsars than the more slowly rotating ones. We note that with our model parameters, the pulsar birth spin period increases with increasing magnetic field, but is almost independent of the field in the range $\log B_{\text{NS}}(\text{G}) = 10\text{--}13$ where the vast majority of isolated radio pulsars lie. The magnetic field dependence becomes important in the high-field radio pulsars and magnetar field range.

The observations show that field distribution is intrinsically asymmetric with a low-field tail that is more prominent than the high-field tail. This general behaviour is reproduced by our assumed bi-Gaussian flux distribution. Furthermore, the model predicts 26 pulsars with fields $> 10^{13}$ G, in good agreement with the PMBS which shows 23 stars in the same field range.

There have been many previous attempts at synthesizing the population of radio pulsars with different assumptions on neutron star magnetic fields, field decay and initial periods. Some of these investigations have led to the conclusion that the neutron star field distribution cannot be described by a single Gaussian (e.g. Gonthier et al. 2002), and we find a similar result for the magnetic fluxes of their progenitor stars.

The initial–final mass–radius relationship that we have assumed implies that higher-mass progenitors will produce higher-mass neutron stars. These stars will, on average, also have higher magnetic fluxes, and therefore tend to produce higher-field neutron stars. However, the latter effect is counterbalanced by the strongly declining initial mass function which favours low-mass star progenitors, which can also produce high-field neutron stars in the Gaussian tail of the magnetic flux distribution. In order to investigate the mass distribution of active radio pulsars in the Galaxy with periods less than 20 s, we have divided them into two field groups [$\log B_{\text{NS}}(\text{G}) = 10\text{--}13.5$] and [$\log B_{\text{NS}}(\text{G}) > 13.5$]. Our results are shown in Fig. 3 for pulsars with 1374-MHz luminosities ≥ 0.19 mJy kpc². The mean neutron star masses in these groups are 1.45 and 1.6 M_{\odot} , respectively, whilst the mean masses of their progenitors are 12 and 19 M_{\odot} ,

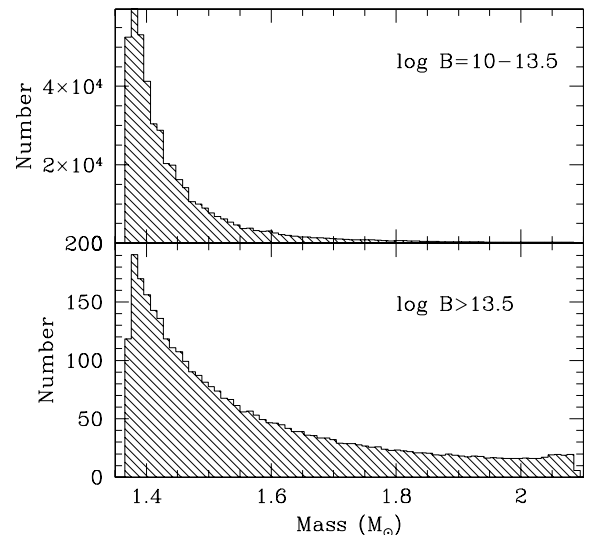


Figure 3. Masses of neutron stars with rotational periods of up to 20 s in the two indicated field ranges.

respectively. The stars in the higher-field bin have a high-mass tail with 54 per cent of the stars extending beyond $1.5 M_{\odot}$ compared to 19 per cent of stars in the same mass range in the lower-field bin. We find that the total number of active pulsars with 1374-MHz luminosities $> 0.19 \text{ mJy kpc}^2$ is 447 000. If we apply the beaming model of equation (10), we find that the number of active pulsars whose beams intercept the Earth reduces to 48 000.

The magnetars are neutron stars that are discovered as X-ray and/or γ -ray sources. They are currently confined to the period range 5–12 s and are young objects (e.g. Gaensler et al. 2001). If one makes the standard assumption of dipole radiation with a braking index of 3, the magnetic fields are in the range $\log B_{\text{NS}}(\text{G}) = 13.8\text{--}15.3$.

We have used our calculations to investigate if the high-field tail of the neutron stars in our model can provide an explanation for the numbers of magnetars that are seen in the Galaxy. Here we use as our cut-off $B_{\text{NS}} = 10^{14} \text{ G}$, since this value is just above the revised quantum critical field of Zhang & Harding (2000) for radio emission. If we isolate the total number of neutron stars with fields in excess of 10^{14} G , and ages of less than 500 000 yr, we find 146 such stars, none of which would be detectable as radio pulsars. If we now limit the age to 100 000 yr, our modelling yields 24 magnetars in the Galaxy with periods from 5 to 12 s and eight magnetars with periods $> 12 \text{ s}$, five of which have periods between 12 and 15 s. Thus, the number declines rapidly with period outside the observed period range. We note in this context that some magnetars exhibit a large discrepancy between their real ages (as determined through their association with supernova remnants) and their characteristic ages (e.g. AXPs 1E 2259+586 and 1E 1845–0545, Gaensler et al. 2001). This discrepancy is readily explained through our assumption of a P – B relationship, which sees high-field neutron stars being born preferentially at long periods (1–10 s).

Below $B_{\text{NS}} = 10^{14} \text{ G}$, there is an area of overlap where a couple of magnetars have fields and periods that are comparable to those of the high-field radio pulsars (HFRPs) (e.g. Kaspi & McLaughlin 2005). This suggests that there could exist lower-field magnetars ($< 10^{14} \text{ G}$) that eventually evolve into X-ray silent HFRPs of the type currently observed if their radio beams intercept the Earth. We note that it should also be possible to discover ‘hybrid’ young objects with $B_{\text{NS}} < 10^{14} \text{ G}$ exhibiting both magnetar and radio pulsar characteristics. In our analysis, we have counted all these objects as radio pulsars if they pass through our PMBS filtering program.

Finally, we return to the recent evidence for high-mass progenitors in the magnetars 1E 1048–5937 (Gaensler et al. 2005) and CXO J164710.2–455216 (Muno et al. 2006). In the dynamo model, rapid spin ($\sim 3 \text{ ms}$) is required to generate super-strong fields and Heger et al. (2005) argued that it is only the cores of the more massive stars that have this property. This has been used as an argument in favour of the dynamo model, at least for the magnetars. We note that these findings also support our fossil hypothesis, since we predict that magnetars, and more generally high-field neutron stars, originate preferentially from high-mass progenitors.

We conclude by noting that the fossil field hypothesis as formulated by us, and which does not allow for magnetic flux loss in the post-main-sequence evolution, requires a very specific distribution of magnetic fields for massive main-sequence stars. This is shown in Fig. 4 for an assumed dipolar field structure. This distribution has a peak at $\sim 46 \text{ G}$ and low- and high-field wings extending from ~ 1 to $\sim 10\,000 \text{ G}$ with 8 per cent of stars having fields in excess of $\sim 1000 \text{ G}$. The latter group are the progenitors of the highest-field magnetars. The detailed shape of the main-sequence distribution

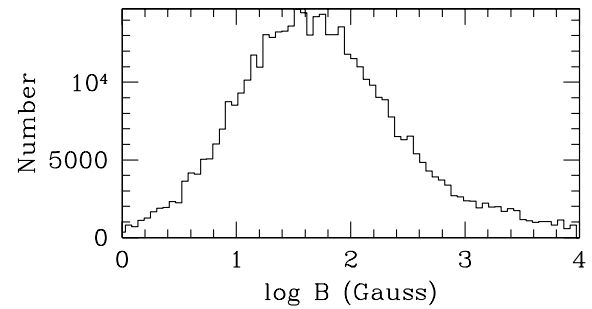


Figure 4. Predicted magnetic field distribution of massive stars ($8\text{--}45 M_{\odot}$) on the main sequence.

shown in Fig. 4 is potentially an observable quantity, and a prediction of our fossil field model.

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