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A novel mechanism for the decay of neutron star magnetic fields

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If the generally accepted picture that the neutrons and protons in the core of a neutron star will be in a (vortex) superfluid state is correct, then the Onsager–Feynman vortices in the neutron superfluid and the Abrikosov vortices in the proton superfluid may be strongly interpinned. We argue that because of this the evolution of the magnetic field will be intimately related to the rotational history of the star. Based on this hypothesis we present a model for the decay of the magnetic fields of neutron stars.

We point out that our model is able to explain for the first time, at least qualitatively, many of the outstanding questions such as (i) the exponential decay of the field in young pulsars, (ii) preponderance of binaries among low-field pulsars, (iii) why very old ($>10^9$ yr) neutron stars retain substantial residual fields and what determines this residual value, etc.

SOON after pulsars were discovered Gunn and Ostriker[1] conjectured that their magnetic fields may be decaying exponentially with a time constant of a few million years. This was motivated by the need to explain the secular decrease in the spin-down torque acting on the pulsar (over and above that due to period lengthening). This idea did not gain immediate credence because it was difficult to reconcile such a rapid decay of the magnetic field with the expected superconducting properties of the interior[2]. In principle, as Gunn and Ostriker themselves pointed out, the decay of the torque acting on the pulsar could also be due to a tendency of the magnetic and rotation axes to align, although they did not favour it. Recent measurements of the obliqueness angle for about 150 pulsars now seem to rule out this possibility[3,4]. Thus, despite the theoretical difficulty in understanding the decay it now appears that the distribution of the measured periods and derived magnetic fields of nearly 500 pulsars is best explained by the hypothesis that the magnetic fields of the population of normal pulsars decay rather rapidly.

There is also circumstantial evidence that this decay may continue for sufficiently long for the magnetic field to decrease to a value of the order of 5×10^8 G. This

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evidence comes from the binary and millisecond pulsars. Most of the pulsars in binaries with massive companions (like PSR 1913+16), as well as the millisecond pulsars with low-mass companions, have anomalous combinations of short periods and low magnetic fields. In recent years this has been understood in terms of the following 'recycling' scenario. The basic idea is that despite their short periods these are very old neutron stars compared to the normal population of pulsars. Their magnetic fields are small because they have decayed substantially during the time between the birth of the neutron star and the onset of mass transfer from the companion. This argument that these are not young pulsars born with low fields has been strengthened by the recent detection of the optical companions of two of these binary pulsars, from which it has been inferred that the pulsars must be very old[5]. The periods of these very old pulsars are short because they have been spun up owing to accretion from the companion (for a more detailed account of this recycling scenario see, for example, ref. 3). But the millisecond pulsars, while providing an important clue about field decay, have also added an extra twist! It is now fairly well established, both from evolutionary scenarios, as well as the direct estimates of the ages of their companions, that millisecond pulsars must have lifetimes in excess of 10^9 years. This should be contrasted with a lifetime $\sim 10^7$ years for the population of the normal pulsars. From this it immediately follows that the observed fields of these millisecond pulsars must be some sort of asymptotic or residual fields[6,7]. That is, whereas the small magnetic fields of these pulsars may be due to decay from original values of $\gtrsim 10^{12}$ G, for some reason or the other this decay seems to effectively stop; otherwise, given their age and the rapid exponential decay mentioned earlier, their fields should have practically disappeared.

Does this asymptotic field have a universal value? Apparently not. Whereas all the millisecond pulsars in the disc of the galaxy have very nearly the same fields, PSR 0655+64 which is as old as the millisecond pulsars has a magnetic field which is more than an order of magnitude larger than that of the millisecond pulsars[5]. This raises the interesting question as to what determines the value of the asymptotic fields of neutron stars.

So far we have dealt with the evidence that suggests that magnetic fields decay substantially (in some cases by a factor of $\sim 10^4$) over timescales of $\leqslant 10^9$ yr. But it now appears that there may be another class of very old neutron stars which show no field decay at all! The tantalizing evidence for this comes from some of the gamma ray bursters. These show features in their X-ray spectra which, if interpreted as the cyclotron line and its harmonics, imply magnetic fields of $\sim 10^{12}$ G (ref. 8). This is very surprising because if gamma ray bursters are neutron stars then the isotropy of their distribution implies that they must be very old[9]. If such high inferred fields turn out to be typical of gamma ray bursters then one will be faced with the difficult question as to why there is a second population of neutron stars whose fields do not decay!

These are some of the questions that any suggested mechanism for field decay must answer. Although there have been several attempts to understand the mechanism of field decay, none of the suggestions made so far have satisfactory answers to the questions raised above (a summary of some of the recent literature can be found in ref. 3). In this paper we wish to advance a new mechanism which, as we shall argue, can, in principle, answer many of the questions.

2. The mechanism

Our basic postulate is that the mechanism of field decay is related to the slowing down of the neutron star[3]. Following the original suggestion by Migdal[10] it is now generally accepted that the neutrons in the interior of a neutron star are in a superfluid state, and that the protons form a type II superconductor[11,2]. Because of the rotation of the star the superfluid will be in a vortex state, i.e. threaded by quantized *vortices* with circulation $h/2m_n$, where h is Planck's constant and m_n the mass of the neutron[12,13]. The total number of vortices is related to the angular velocity Ω of the crust through the relation

$$N_v = (\Omega R)(2\pi R)/(h/2m_n) \approx 2\times 10^{16} P^{-1}, \quad (1)$$

where R is the radius of the neutron star and P the period in seconds.

There is a second set of vortices in the interior. As mentioned above, the protons in the interior are expected to condense into a type II superconducting state. Although the initial field of the neutron star ($\sim 10^{12}$ G) is much less than the estimated **lower** critical field H_{c1} ($\sim 10^{15}$ G), Baym *et al.*[2] have argued that because of the very high electrical conductivity of the normal state superconductivity will nucleate in a **vortex state** at constant B. That is, the superconductor will allow the magnetic field to coexist, but confined to a lattice of *fluxoids*, each with a quantum of flux $\phi_0 = hc/2e$. The number of such quantized flux tubes is given by

$$N_f = \pi R^2 B/\phi_0 \approx 10^{31} B_{12}, \quad (2)$$

where B_{12} is the magnetic field in units of 10^{12} G. Flux can be expelled from the superconducting region only if the fluxoids can migrate to the crust. The characteristic timescale for this process may be more than the age of the universe[2].

Although the superfluid *vortices* and the *fluxoids* have been invoked to understand some aspects of the rotational dynamics and the decay of the magnetic field respectively[14-16], the consequences of the **interaction** between these two families of vortices has not been seriously explored so far. Muslimov and Tsygan[16] were the first to point out that the *vortices* and *fluxoids* may be strongly interpinned. More recently Sauls[17] has stressed that such pinning may have several interesting consequences. The possibility that the evolution of the magnetic field may be linked to the rotational history of the neutron star through such pinning was first pointed out by Srinivasan[3]. Here we shall elaborate on this suggestion, as well as give some estimates.

In order for the field trapped in the interior to decay at all the fluxoids must somehow migrate to the crust where the field can decay due to ohmic dissipation. Muslimov and Tsygan[16] argued that this may happen owing to buoyancy forces acting on the fluxoids. The recent estimate due to Jones[18] suggests that this process of flux expulsion, limited by drag forces, may be quite efficient. However, various effects that have been neglected so far, such as pinning of the fluxoids at the inner crust, may drastically reduce the importance of buoyancy forces. Also, because of the dependence of the gap energy on the density, the fluxoids may experience *buoyancy* only in the outer regions of the core; in the inner region the fluxoids may actually migrate towards the centre of the star[19]. In any case, in what follows we shall assume that the tendency of the fluxoids to migrate to the surface is strongly inhibited by the pinning of the fluxoids to the vortices in the (core) neutron superfluid.

If so, why and how does the magnetic field decay? As the neutron star spins down the superfluid core responds by destroying the vortices in a proportionate way; this happens by a *radial outward flow* of the vortices and the annihilation of the required number at the interface between the inner crust and the superfluid core. In this process the fluxoids pinned to them will also be transported to the crust, where the field can decay due to ohmic dissipation. Thus there are **two timescales** in this mechanism: (i) the timescale for the expulsion of the field from the interior to the crust; this is related to the spin-down timescale τ_{sd}; and (ii) the timescale for ohmic decay in the crust, τ_d, which is believed to be $\sim 10^6$ yr (ref. 20). The temporal behaviour of the magnetic field will depend upon whether τ_{sd} is greater or smaller than τ_d. As we will see, both regimes are of interest. In the previous section it was mentioned that one of the difficulties with the currently available models for field decay is in explaining the longevity of millisecond pulsars since in these models the decay is exponential with a **single time constant** of $\sim 10^6$ yr. The present model does not suffer from this difficulty (see Section 4).

3. Some estimates

Assuming that a fluxoid can pin on a vortex, the first question to ask is how effective this is likely to be. In this section we shall give some simple estimates and argue that the vortices, although only $\sim 10^{16}$ in number in a typical pulsar, can entrain most, if not all, of the $\sim 10^{31}$ fluxoids.

The pinning of vortices to point defects has been invoked to explain a variety of phenomena ranging from the critical state of hard superconductors[21] to glitches in pulsars[14]. That there is pinning at all can be traced to local modifications of the penetration depth (say, by strain), local modifications of the superfluid condensation energy, etc. But unfortunately the details have been worked out only at a phenomenological level[22]. The physics of the interaction of a vortex with a fluxoid is even less understood. Since these two vortices are in two different superfluids, unless the gap energy or the density of each fluid changes owing to the interaction, there will be no interaction energy. However, a simple estimate due to Sauls[17] suggests that the interaction energy may be large. The pinning energy of a fluxoid–vortex intersection due to proton density perturbation in the centre of a fluxoid may be estimated as follows:

$$\epsilon_{\rm PIN} \sim n_n \frac{\Delta_p^2}{E_{Fp}^2} \frac{\Delta_n^2}{E_{Fn}} (\xi_n^2 \xi_p), \tag{3}$$

where Δ is the energy gap, E_F the fermi energy, ξ the coherence length and n the number density; the subscripts p and n refer to protons and neutrons, respectively. For typical values of the above parameters this pinning energy is $\sim$(0.1–1) MeV per connection[17]. A rough estimate of the *pinning force* per connection, $F_{\rm PIN}$, may be obtained by dividing the above pinning energy by the neutron coherence length ξ_n, which is a measure of the size of the interaction region:

$$F_{\rm PIN} \approx \frac{\epsilon_{\rm PIN}}{\xi_n} \sim (0.1\text{–}1) \times 10^6 \text{ dyne connection} \tag{4}$$

for a typical value of $\xi_n \sim 1.5 \times 10^{-12}$ cm. Thus the pinning force per unit length of the fluxoid is $\sim$(0.1–1) dyne cm^{-1} per connection. If one assumes that the fluxoid is pinned at N_p centres then the total pinning force per unit length $f_{\rm PIN}$ is $\sim$(0.1–1) N_p dyne cm^{-1}. The key question to ask is the following. What is the value of N_p such that the net pinning force on a fluxoid will be large enough to counteract the buoyancy force? The latter force (per unit length) can be estimated from the relation $f_b = -g\varepsilon/C_s^2$, where ε is the energy of the fluxoid per unit length, g the acceleration due to gravity, and C_s the velocity of sound[16]. Since $C_s^2 \sim Rg$ it follows that $f_b \sim \varepsilon/R$. The energy of the fluxoid per unit length can be estimated from the expression

$$\varepsilon=\left(\frac{\phi_0}{4\pi\lambda_p}\right)^2 \ln\left(\frac{\lambda_p}{\xi}\right), \tag{5}$$

where λ_p is the London penetration depth[22]. For values of the parameters appropriate for the proton superconductor, $\varepsilon \sim 10^7$ erg cm^{-1}. This gives us an estimate for $f_b \sim 10$ dyne cm^{-1}. Hence we conclude that, if a fluxoid is pinned at roughly 10 to 100 centres, then the total force due to pinning will prevent the fluxoid from ascending towards the crust owing to buoyancy. Whether or not this obtains in practice is hard to assess at present for the following reason. When one is dealing with only one of the superfluids it may be safe to assume that the vortices form a lattice. But in the present case one is dealing with two superfluids and the detailed geometrical arrangement of the superfluid vortices and the fluxoids is far from clear, particularly since they are expected to interact strongly with one another. It is conceivable that neither set of vortices will form an idealized lattice, nor are the vortices likely to be globally straight. The actual situation may resemble what is shown in Figure 1*b* rather than the idealized geometry of Figure 1*a*. Given this uncertainty one cannot meaningfully estimate the number of fluxoids that are likely to be physically pinned to the Onsager–Feynman vortices. Instead, one can estimate the total number of available pinning sites for the fluxoids. Assuming that the fluxoids are in fact pinned to all the available sites, one can estimate how many of them can be 'trapped' owing to the pinning. The total number of available pinning sites is equal to the maximum number of fluxoids that can be pinned to a single vortex of length $\sim 10^6$ cm times the total number of vortices ($=2\times 10^{16}\,P^{-1}$). At first sight it would seem that the maximum number of fluxoids that will be pinned to a given vortex line will be determined by the mean fluxoid spacing of $\sim 5\times 10^{-10} B_{12}^{-\frac{1}{2}}$cm. But the actual number can be much more than implied by the above mean spacing, and will be limited only by the mutual repulsion between the fluxoids themselves. As is well known[22], at separations d_f large compared to the London penetration depth λ_p this is a weak repulsion $\propto (\lambda_p/d_f)^{\frac{1}{2}} \exp\{-d_f/\lambda_p\}$. A simple estimate which takes into account both the pinning force and the repulsive force suggests that the mean distance between the **pinned** fluxoids can be as small as 2×10^{-11} cm (for comparison, $\lambda_p \sim 0.9\times 10^{-11}$ cm). Hence in the estimate given below we shall assume that d_f is $\sim(2\text{–}20)\times 10^{-11}$ cm (the larger of the two estimates corresponds to the *mean* spacing for $B_{12}\sim 2$). This gives $\sim(10^{32}\text{–}10^{33})P^{-1}$ available pinning sites in the neutron superfluid. Therefore the number of 'trapped fluxoids' (see the discussion above) will be $\sim(10^{30}\text{–}10^{32})P^{-1}$. (It should be borne in mind that not all of these 'trapped fluxoids' need to be physically pinned; fluxoids pinned at a large number of centres can inhibit the motion of the neighbouring ones.) If this estimate is reasonable then the 'trapped magnetic field' will be $\sim(10^{11}\text{–}10^{13})P^{-1}$ G, i.e. most of the fossil field may be trapped in the interior owing to their entanglement with the Onsager–Feynman vortices.

4. The evolution of the magnetic field

If the above conclusion is correct then the decay of the magnetic field must be intimately related to the slowing down of the neutron star, i.e. $B(t) \propto \Omega(t)$. If the slowing down of the neutron star is due to pulsar activity

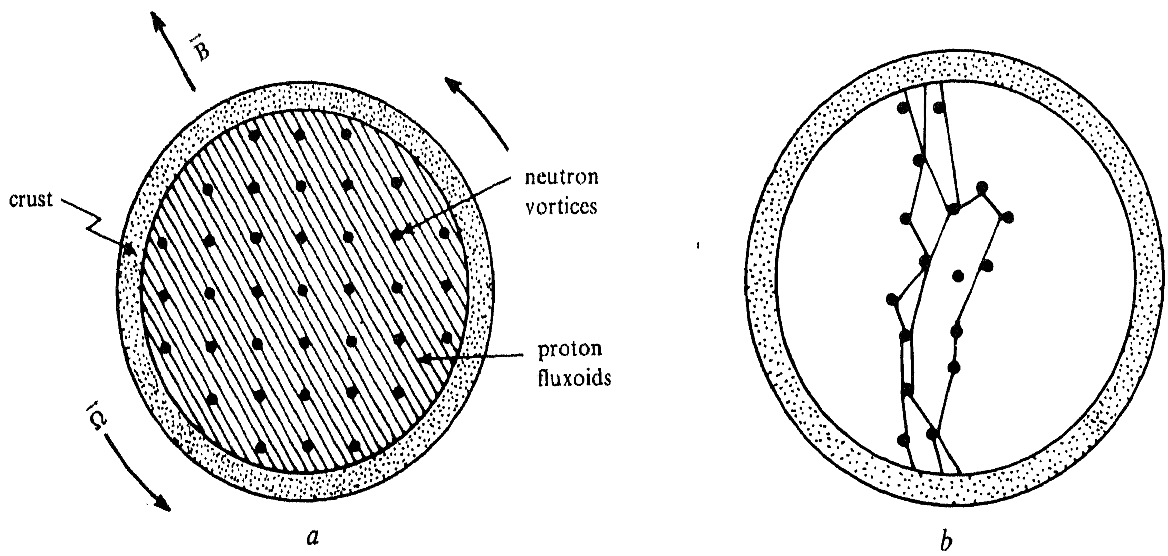

Figure 1. *a*, A view of the equatorial plane of a rotating neutron star showing an idealized geometry of the arrangement of the Onsager–Feynman vortices (parallel to the rotation axis) in the neutron superfluid and the Abrikosov vortices (parallel to the magnetic axis) in the proton superconductor. For the purpose of illustration the magnetic axis has been assumed to be perpendicular to the rotation axis. For the magnetic field to decay the fluxoids must migrate to the crust where, because of the finite conductivity, the field can decay. *b*, A more realistic state of affairs in the presence of strong interaction between the vortices in the two superfluids.

(namely the emission of a relativistic wind and/or magnetic dipole radiation), then it is possible to derive a law for the evolution of the magnetic field. For example, if one adopts the standard dipole model for pulsar braking[1], viz.

$$-\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}I\Omega^2\right)=L=\frac{2}{3c^3}B^2R^6\Omega^4, \tag{6}$$

then if $B(t)\propto\Omega(t)$ [which is only valid for times $t>t_0$ such that the spin-down timescale τ_{sd} is greater than τ_d ($\sim 10^6$ yr) the ohmic dissipation timescale in the crust], it follows that

$$B(t)=B(t_0)\left[1+\frac{2(t-t_0)}{\tau_{sd}(t_0)}\right]^{-\frac{1}{4}}, \tag{7}$$

where $\tau_{sd}(t_0)=[8B^2(t_0)\Omega^2(t_0)R^6/3Ic^3]^{-\frac{1}{2}}$ is the spin-down timescale at $t=t_0$. $B(t_0)$ and $\Omega(t_0)$ refer to the value of the magnetic field and angular velocity, respectively, at t_0, I the moment of inertia, R the radius, and c the velocity of light. Thus at late times $B(t)\propto(t/t_0)^{-\frac{1}{4}}$, since $\tau(t_0)\sim t_0$. With such a slow rate of decay it is hard to see how the fields of millisecond pulsars could have decayed to $\sim 5\times 10^8$ G even given a Hubble time. Moreover, it is hard to account for the decay of pulsar fields by a couple of orders of magnitude within the lifetime of a pulsar $\sim 10^7$ yr. Hence, if the mechanism described in the previous section is the operative one, then one is forced to conclude that the magnetic fields of isolated pulsars cannot decay significantly!

4.1 *Neutron stars in binaries*

The above difficulty is overcome if the neutron star in question is in a binary system. The main evidence that neutron stars in binaries can be slowed down to long periods comes from the dozen or so X-ray pulsars with periods ranging from 104 s to 835 s (see, for example, the review by Henrichs[23]). One of the mechanisms for understanding why such a spin-down occurs was proposed by Illarionov and Sunyaev[24] even before the first slow X-ray pulsar was discovered. They argued that while the companion of the neutron star is in an evolving phase the magnetosphere of the neutron star will act as a 'propeller', throwing out the stellar wind matter from the companion, thus preventing it from accreting onto the neutron star; as a consequence of this the neutron star will slow down. Such a spin-down will continue until the corotation radius becomes equal to the magnetospheric radius, at which stage wind accretion will set in. But as Henrichs[23] has pointed out, there are several reasons for doubting whether such an electromagnetic torque can slow down a neutron star to the periods mentioned above within the evolution time of the companion. Faced with this difficulty, several alternative mechanisms have been suggested. According to Gosh and Lamb[25], for example, spin-down to long periods may also occur after the onset of accretion owing to accretion torques. Regardless of which of the proposed mechanisms is relevant, there is direct observational evidence that neutron stars with massive companions are slowed down to rather long periods before they are spun up during the Roche lobe overflow phase. Unfortunately there is no direct observational evidence for this intermediate phase in the rotational history of a neutron star in a low-mass binary. In analogy with their counterparts with massive companions, we shall assume that these neutron stars, too, will be slowed down. The physical mechanism is not clear at present. The winds from low-mass stars are never strong, except perhaps when they become giants; perhaps the braking will occur in this phase. But preliminary estimates suggest that even the weak wind in the main sequence phase will be effective, especially when the orbital separation is less than $\sim 30R_\odot$. In the absence of detailed theoretical studies to guide us we shall assume that given the much longer evolutionary timescale for low-mass stars, neutron stars with low-mass companions will be braked to much longer periods.

Let us now return to the question of field decay. Earlier we had concluded that if the expulsion of the field from the interior is linked to the slowing down of the neutron star then the **fields of isolated pulsars cannot decay significantly**. On the other hand, it follows from the above discussion that **fields of binary pulsars should decay substantially**.

4.2 *The residual field*

As mentioned earlier, two of the key questions any theory of field decay must address are (i) why do very old neutron stars—such as the millisecond pulsars—still retain substantial fields, and (ii) what determines this 'asymptotic' value. Both these questions find a natural explanation in our model. For a pulsar in a binary system there are three distinct phases. During the first phase of pulsar activity there is hardly any decay of the field since this phase does not last very long. Much of the field decay is due to the braking experienced before the neutron star becomes a powerful X-ray source. Once the mass transfer phase ends, and the neutron star starts functioning as a pulsar again, any further decay of the field will be governed by the new spin-down timescale of the pulsar. Because of the low field the spin-down timescale in its second life will be very long; hence there will be essentially no further decay of the field. **The value of this 'residual field' will be determined by the maximum period to which the neutron star was spun down.** This is illustrated in Figure 2. The

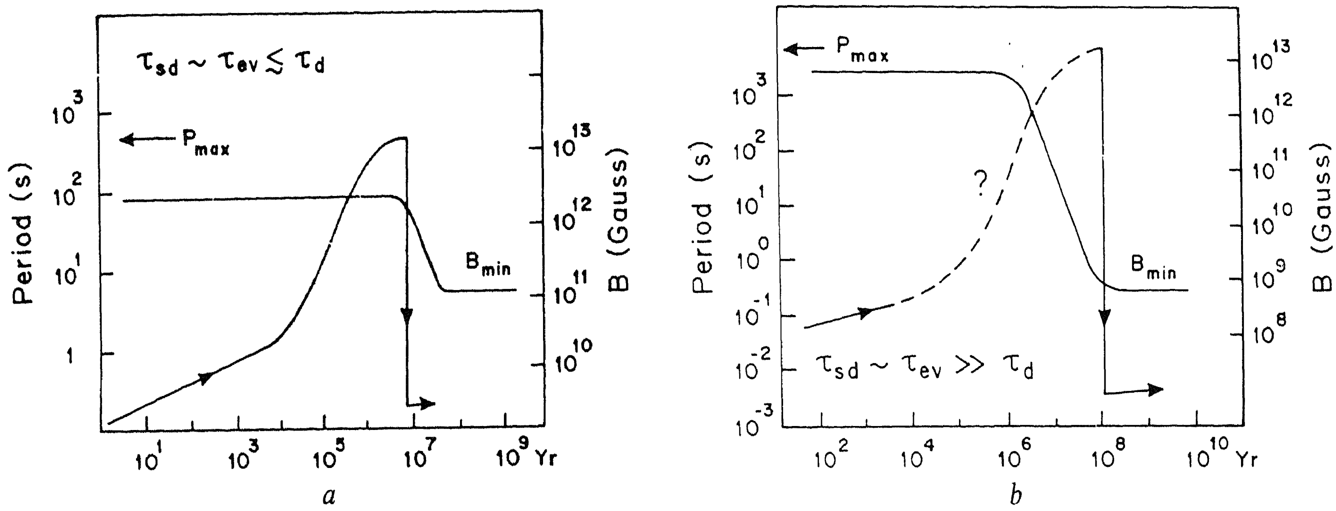

Figure 2. The rotational history and the evolution of the magnetic field of neutron stars in binaries. The first-born neutron star in a binary will be slowed down to very long periods owing to the electromagnetic torque exerted by the stellar wind from the companion. After the companion fills its Roche lobe, heavy accretion onto the neutron star will set in and in the process the neutron star will be spun up to an equilibrium period determined by its magnetic field and the accretion rate. After accretion stops, the spun-up neutron star will, once again, function as a pulsar. Figure *a* is appropriate for a massive companion whose evolution time (τ_{ev}) is $\lesssim \tau_d$ the ohmic dissipation timescale in the crust. In this case the decay of the field will lag behind the rapid period lengthening. The asymptotic field will be determined by the maximum period to which the neutron star was slowed down. Figure *b* is for the case when τ_{ev}'$\gg \tau_d$; this may obtain in low-mass binaries. Here, field decay will 'track' the period of rotation.

rotational history of a neutron star in a massive binary[26] and the consequent evolution of the magnetic field are shown in Figure 2*a*. Pulsar activity ceases when the magnetospheric radius becomes smaller than the light cylinder. After this the electromagnetic torque due to the steller wind from the companion rapidly slows down the neutron star. The maximum period reached depends on the evolution time of the companion. After Roche-lobe overflow begins the neutron star will be spun up to an equilibrium period determined by the accretion rate and the magnetic field[27,28]. After the mass transfer ceases and the debris clear away, the spun-up neutron star will once again function as a pulsar. Turning next to the evolution of the field, it is interesting to note that the decay of the magnetic field is not 'in phase' with the lengthening of the period. This is because in a massive binary the duration of the rapid braking phase (which will only be a fraction of the evolution time of the companion) will be small compared to the ohmic dissipation timescale in the crust ($\gtrsim$ a million years). Figure 2*b* deals with the other extreme case, viz. the evolution timescale of the companion (more precisely the braking timescale) is much longer than the ohmic decay timescale. In this limit the magnetic field will 'track' the period. This may be the case in low-mass binaries.

In the past the evolution of neutron stars has often been represented in the *B–P* plane[29,30]. Hence it may be useful to display the evolution shown in Figure 2 in the *B–P* plane. This is shown in Figure 3. It may be recalled that the first-born neutron star in a **massive binary** is likely to be detected as a pulsar only in its second life (this is because even the weak stellar wind from the companion is enough to absorb the radio

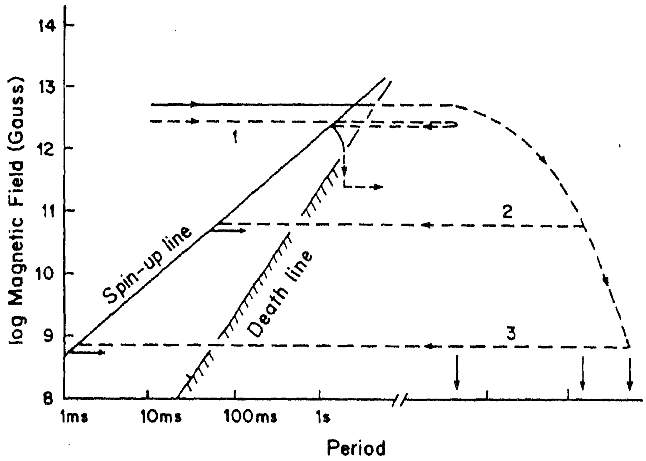

Figure 3. The evolution of neutron stars in the magnetic field–period plane. The curve labelled '1' corresponds to the case discussed in Figure 2*a* ($\tau_{sd} \sim \tau_{ev} \lesssim \tau_d$). Curves '2' and '3' refer to two different situations in both of which $\tau_{sd} \gg \tau_d$. The 'spin-up line' is the equilibrium period line corresponding to accretion at the maximum possible Eddington rate. The 'death line' represents the turn-off of pulsar activity.

radiation emitted by the pulsar). In the majority of cases the second supernova will disrupt the binary, resulting in two isolated neutron stars. According to our model, the magnetic field of the **first-born** pulsar will decay because of the flux expulsion from the interior that occurred during the slow-down phase. The magnetic field of the second-born pulsar is not expected to decay significantly and its trajectory will be essentially horizontal (of course, if a fraction of the field is not entangled with the vortices then **if** buoyancy effects are important, then this field will escape to the crust and decay. This possibility has not been included in the figure). As for the pulsars from low-mass binaries, such as the millisecond pulsars, they will essentially evolve with constant field as conjectured earlier[6].

It was mentioned above that the fields of spun-up pulsars will not decay significantly owing to their long spin-down timescales. It may be worth pointing out that there is an additional effect which will further stabilize their fields. When a dead pulsar is spun up, new vortices will be created in the neutron superfluid and these will move radially inward. This will increase the entanglement between the vortices and the fluxoids, and also push the field further in towards the core. This will be particularly important for pulsars spun up to ultra-short periods.

5. Summary and discussion

The mechanism for field decay advanced and discussed in this paper is distinct from all previous suggestions. Following the pioneering arguments made more than two decades ago[10-12] we assume that the neutrons in the core are in a superfluid state, the protons form a type II superconductor, and the magnetic field threads the interior as flux tubes. Our basic point is that these fluxoids and the Onsager–Feynman vortices in the neutron superfluid may be strongly interpinned so that the evolution of the magnetic fields is related to the rotational history of the neutron star. As the neutron star slows down the neutron vortices will move radially outwards and be annihilated at the interface with the crust. In the process they will drag the fluxoids entangled with them towards the crust. The field thus transported to the crust will decay there owing to ohmic dissipation.

In this scenario the **fields of isolated neutron stars will not decay significantly** since they will not slow down very much for the above process to be important. But **since the first-born neutron stars in binaries can and will slow down significantly their fields are expected to decay significantly**. Since further decay due to slow-down after the binary phase is over is unimportant, these neutron stars will have residual fields which will be determined by the maximum period to which they were spun down before being spun up. We wish to emphasize that the details of the decay of the magnetic field and, in particular, the strength of the residual field are intimately related to the actual history of the neutron star in the binary. For example, a neutron star born in a low-mass binary owing to the accretion-induced collapse of a white dwarf may have a different (possibly higher) residual field than others born in standard supernovae. We plan to address these more detailed issues in subsequent publications.

Comparison with observations

(i) The most striking thing about the distribution of the derived fields of nearly 400 pulsars is that the overwhelming majority of pulsars with very low magnetic field (say, $< 5 \times 10^{10}$ G) are in binaries. In fact, if one leaves out the very recently discovered pulsars in globular clusters, the only solitary ultra-low-field pulsar is the 1.5 millisecond pulsar PSR 1937+21. Even in this case there are very strong reasons to believe that this pulsar, like the other millisecond pulsars, was spun up in a binary but eventually the companion got disrupted (see ref. 31 for a summary of the arguments). Most of the pulsars in globular clusters are also in binaries. The few solitary ones can easily by understood in terms of the binaries being disrupted due to stellar encounters in the dense environment of a globular cluster. **The fact that most of the low-field pulsars are in binaries lends strong support to our model.**

(ii) The inferred magnetic field of $\sim 5 \times 10^{12}$ G for the neutron star in the X-ray binary Hercules X-1 (ref. 32) has often been cited as a counterexample for the field decay hypothesis since this is believed to be an old system. In our opinion there are two possible reasons for the relatively high field. At present the neutron star is accreting from a disc and the rotation period is 1.2 s. If for some reason it was not slowed down significantly before disc accretion began then one would not expect a low field. Alternatively, if the slow-down occurred only recently ($\lesssim$ a few million years), then the consequent field decay will occur only in the future.

(iii) Most models constructed to explain the exponential decay of the magnetic fields of young pulsars over a timescale of a few million years cannot explain why this decay should stop, or dramatically slow down. The most attractive feature of our model is that it provides, for the first time, a natural explanation for the residual fields of old neutron stars. The fact that the residual fields of millisecond pulsars is smaller than those of the binary pulsars with massive companions (such as PSR 1913+16, PSR 0655+64, etc.) can be understood in our scenario if neutron stars in low-mass binaries are slowed down to much longer periods than in massive binaries.

(iv) Although the low fields of binary pulsars may be understood in terms of our model it remains to be explained why the population of young pulsars, almost all of them solitary, show exponential field decay with a time constant of a few million years. This can be easily understood if the majority of pulsars are born in massive binary systems. Such systems will produce two pulsars and the binary will get disrupted as a result of the second supernova explosion. The second-born pulsar will not exhibit field decay but the first-born pulsar will show field decay (see Figure 3). Since in these systems the evolution time of the companion is $\lesssim$ the ohmic dissipation timescale in the crust, the actual decay will occur *after* the system has been disrupted and the decay will be exponential. Recently two independent arguments have been advanced which support our hypothesis that the majority of pulsars may be born in massive binary systems. (1) The large number of transient X-ray sources discovered by the GINGA satellite[33], and identified with B-emission X-ray binaries, suggest that the birth rate of these systems may be much higher than that of the standard massive X-ray binaries. (2) The most plausible explanation to date for the origin of the observed distribution of pulsar velocities is that the pulsars acquire their velocities owing to the disruption of the binaries. Again, this hypothesis requires that most pulsars are born in binaries[34,26,35].

(v) Our model provides a simple explanation for why the gamma-ray bursters, which are presumably very old neutron stars, have high magnetic fields. If these are *solitary* neutron stars then, as explained in Section 4, their fields should **not** have decayed significantly!

Finally, we wish to make a few general remarks. While the mechanism for field decay suggested by us is very attractive it should be emphasized that our extremely rough estimates should be regarded as the first attempt to explore the many rich consequences of the pinning hypothesis. Before any detailed analysis of the maximum magnetic field that can be trapped in the interior owing to pinning with the vortices can be undertaken, a better estimate of the pinning energy is required. Also, a clearer picture of the geometrical arrangement of the fluxoids and the core superfluid vortices is needed. It is conceivable that the fluxoids are bound together into 'bundles' as appears to be the case in hard superconductors[21]. If the 'bundles' are of the dimension of the London penetration depth then each bundle might comprise several hundred quantized flux tubes. This might make pinning of the magnetic field to the vortices much easier.

In this paper we have explored the implications of the rotational history for the evolution of the magnetic field. If the effects discussed in this paper are important then it goes without saying that the pinning of the vortices and fluxoids will also have interesting implications for the **rotational dynamics.** The unpinning and repinning of these two sets of vortices may, in fact, be responsible for the phenomenon of glitching[16,17] rather than the pinning of the crustal superfluid as suggested by Anderson and Itoh[14]. The pinning of fluxoids and vortices will also have important implications for the secular alignment of the magnetic axes and the rotation axes of pulsars.

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