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The Evolution of the Magnetic Fields of Neutron Stars

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Abstract. Observational evidence, and theoretical models of the magnetic field evolution of neutron stars is discussed. Observational data indicates that the magnetic field of a neutron star decays significantly only if it has been a member of a close interacting binary. Theoretically, the magnetic field evolution has been related to the processing of a neutron star in a binary system through the spin evolution of the neutron star, and also through the accretion of matter on the neutron star surface. I describe two specific models, one in which magnetic flux is expelled from the superconducting core during spin-down, via a copuling between Abrikosov fluxoids and Onsager-Feynman vortices; and another in which the compression and heating of the stellar crust by the accreted mass drastically reduces the ohmic decay time scale of a magnetic field configuration confined entirely to the crust. General remarks about the behaviour of the crustal field under ohmic diffusion are also made.

Key words: Neutron Stars – Pulsara – Magnetic Field

1. Introduction

The evolution of the magnetic field influences practically all aspects of neutron star evolution, such as the active life times of radio pulsars and the distribution of their periods and luminosities, the rate of cooling of the star, spin-up and spin-down processes in accreting neutron stars and so on. In particular, the evolutionary link between young neutron stars similar to the majority of radio pulsars, and X-ray binaries and recycled binary pulsars is critically dependent on the magnetic field evolution.

Soon after the discovery of pulsars, Gunn and Ostriker (1970) suggested a very simple picture of the magnetic field evolution – an exponential decay with the time constant of a few million years, due to ohmic dissipation of currents in the stellar

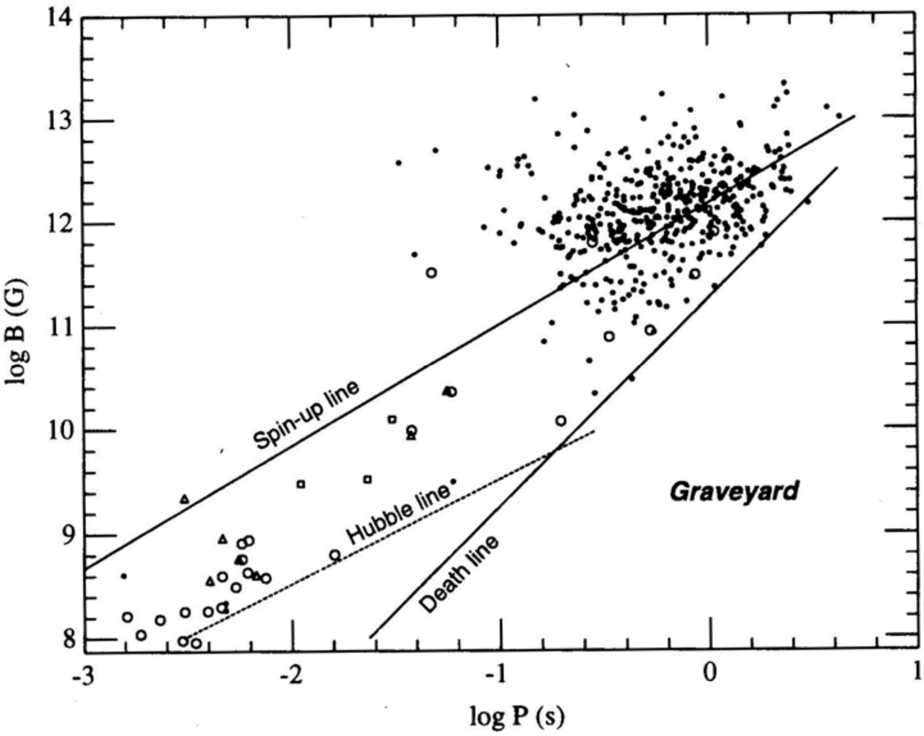

Figure 1: The magnetic fields and periods of known pulsars. Filled dots indicate isolated pulsars and open circles binaries, both in the galactic disk. Isolated pulsars in globular clusters are shown as triangles and binaries in globular clusters as squares. The spin-up line shows the minimum period to which a neutron star can be spun-up in an Eddington-limited accretion. Pulsar activity ceases to the right of the death line, and the spindown age of a pulsar equals 10^{10} yr on the Hubble line.

crust. Opinion has, however, substantially diverged from this view over the past decade with the accumulation of new observational data.

In this lecture I shall first briefly review the available facts on which the current picture of magnetic field evolution is based (section 2) and then describe a few theoretical models currently under development (sections 3 and 4).

2. Observational facts

Conclusions regarding the evolution of magnetic fields of neutron stars are based primarily on the following facts (see Bhattacharya 1994; Bhattacharya and Srinivasan 1995 for more detailed discussions):

- Most isolated pulsars have magnetic fields $B \sim 10^{12}$ G, with a dispersion of about an order of magnitude.

- Most pulsars in binaries have lower field strength, going down to ~ 10^8 G (see fig. 1).

- Recycled pulsars processed in low-mass binary systems (i.e. pulsars with low-mass white dwarf companions in circular orbits) have, in general, lower field strengths than those processed in massive binaries (i.e. those with heavy white dwarf or neutron star companions).

- Most pulsars in globular clusters have field strengths $\lesssim 10^{10}$ G.

- Massive X-ray binaries tend to have neutron stars with strong fields, in some cases cyclotron lines have been observed indicating local field strengths of order 10^{12} G.

- Low-mass X-ray binaries do not show X-ray pulsations, but exhibit thermonuclear bursts instead. This is attributed to low surface magnetic fields of the neutron stars in them.

- Several pulsars with white dwarf companions argue for a long-term stability of their fields at levels ranging from ~ 10^8 G to ~ 10^{11} G.

One of the classical arguments for spontaneous decay of the magnetic fields of isolated pulsars, the so-called kinetic age–characteristic age relation (Lyne, Anderson and Salter 1982) has come under criticism of late, and it appears that given the uncertainties in the estimation of the kinetic age, and the selection effects involved in the detection of pulsars this relation is consistent with no decay of the magnetic fields of isolated pulsars (Bailes 1989, Lorimer 1994).

Statistical studies of the isolated pulsar population have often claimed the evidence of magnetic field decay in time scales of a few million years (see, e.g. Narayan and Ostriker 1990) . This has, however, not been an unanimous conclusion: several authors obtained results to the contrary (e.g. Krishnarnohan 1987, Srinivasan 1991, Michel 1992). The latest detailed studies in this regard appear to consistently argue that no appreciable magnetic field decay occurs during tha active life times of isolated radio pulsars (Bhattacharya et al 1992, Wakatsuki et al 1992, Lorimer 1994). Further, the "asymmetric drift" in the galactic plane displayed by pulsars (Phinney, this meeting) also argues for their magnetic fields being long-lived.

Two key points emerge from the above discussion: (*a*) that there is a large preponderance of binaries among low-field pulsars (fig. 1), and (*b*) that the magnetic fields of isolated pulsars, as well as those of binary pulsars well after recycling, appear to be long-lived and stable. These two points have been synthesised in a new hypothesis regarding the evolution of neutron star fields: that a significant field decay occurs only as a result of the interaction of the neutron star with its binary companion (Bailes 1989). This view is now rapidly gaining ground.

In the rest of this article I shall describe attempts to physically relate the evolution of the magnetic field with the interaction of the neutron star and a close binary companion.

3. Magnetic field in the neutron star interior

The neutron star is believed to consist of a core composed of superfluid neutrons and superconducting protons, covered by a crust of varying composition – the boundary between the two being at a density ~ 2.4 × 10^{14} g cm^{-3} (see e.g., Pines 1987). While the total stellar radius is ~ 10 km, the extent of crust is ~ 1 km.

While we know that a neutron star is strongly magnetized, we have little indication of where in the stellar interior this field may reside. In the literature, therefore, two classes of models are being considered — one in which the initial magnetic field is spread through the star more or less uniformly, and hence most of it penetrates the core region, while in the other the initial magnetic field is confined to the thin outer layers of the crust. The former is likely to be appropriate if the magnetic field is a fossil remnant of that in the neutron star progenitor, while the latter would be the case if the magnetic field is generated by processes such as thermomagnetic instabilities (Urpin and Yakovlev 1980; Blandford et al 1983) after the formation of the neutron star.

The structure of the interior field would be very different in these two cases. If the field penetrates the superconducting core, the field would be carried by Abrikosov fluxoids in the proton superconductor (see Sauls 1989 and Bhattacharya and Srinivasan 1995 for detailed reviews). These fluxoids have cores of size ~ 10^{-12} cm consisting of normal proton fluid, through which the magnetic field passes. Outside the core superconducting currents screen out the field over the London length, ~10^{-11}cm. The field strength at the core of these fluxoids reach the lower critical field of the superconductor, ~ 10^{15} G. The total number of such fluxoids in the core of the neutron star is ~ $10^{31}B_{12}$, where B_{12} is the strength of the average magnetic field in units of 10^{12} G.

If the field is crustal, the accompanying currents are assumed to be wholly confined to the region where protons are in a normal state, and most of the initial field is considered to be anchored at densities below the neutron drip (see Blandford et al 1983, Romani 1990, Urpin and Muslimov 1992).

4. Models for magnetic field decay

Proposed physical models that relate the decay of the magnetic field of a neutron star with the evolution of the star in a binary systems can be broadly classified into two categories: one in which the field evolution is tied to the evolution of the spin of the neutron star and the, other in which the accreted mass causes a reduction in the field. In the former category fall models involving the interpinning of the Abrikosov fluxoids and the Onsager-Feynman vortices which carry the angular momentum of the neutron superfluid (Srinivasan et al 1990), and the models involving plate tectonics of the neutron star crust (Ruderman 1991). The latter category includes models involving screening of the neutron star field by the diamagnetic accreted plasma (Bisnovatyi-Kogan and Komberg 1974), an inverse thermoelectric battery (Blondin & Freese 1986), dragging and reconnection of the field by the incoming matter flow (Romani 1990), and enhanced ohmic decay due to the compression and heating of the crustal material as a result of mass accretion (Geppert and Urpin 1994, S. Konar and D. Bhattacharya, in preparation).

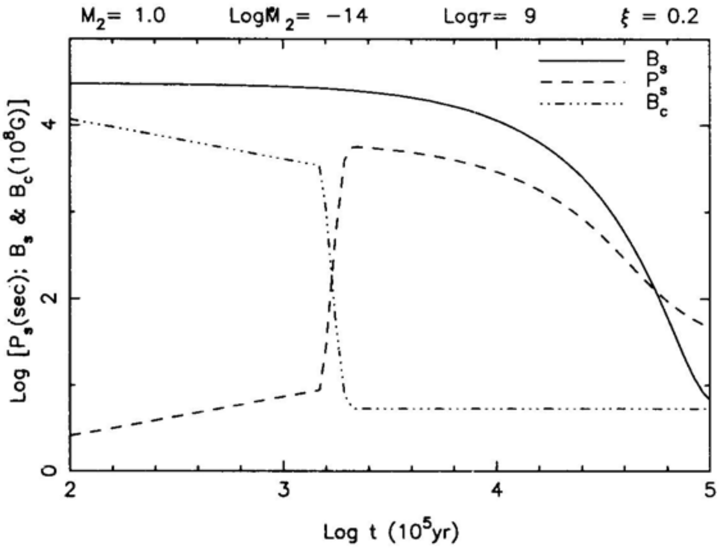

Figure 2: The evolution of the spin period P_s, core magnetic field B_c and surface field B_s of a neutron star in a low-mass binary, according to the spindown-induced flux expulsion scenario. M_2 is the secondary mass in solar masses, $\dot{M}_2$ is the wind rate of the secondary in $M_\odot$ /yr, τ is the ohmic decay time scale in the crust in yr and ξ is an efficiency factor that determines the degree of angular momentum transfer in the interaction between the wind matter and the neutron star magnetosphere. From Jahan Miri and Bhattacharya (1994).

In what follows I shall discuss only two of the above models, namely the decay of the core field due to vortex-fluxoid interpinning and the enhanced ohmic decay of crustal field due to accretion. The reader is referred to more extended reviews (e.g., Bhattacharya and Srinivasan 1995) for discussion on other models.

4.1 *Spindown-induced decay of the core magnetic field*

In this section we shall assume that the initial magnetic field of the neutron star passes through the superfluid-superconducting core and is carried by Abrikosov fluxoids in the proton superconductor. As mentioned above, in the core neutron superfluid and proton superconductor coexists, and the angular momentum of this superfluid is carried by quantized Onsager-Feynman vortices. It was pointed out by Sauls (1989) that a strong interpinning may exist between the vortices and the fluxoids due to many-body effects. In addition, there is also a strong magnetic interaction between the vortices and fluxoids (Ruderman 1991, Bhattacharya and Srinivasan 1991, Ding et al 1993). As the neutron star spins down, the vortices reduce in number by moving out, and in the process carry the fluxoids crustward. Once the field is deposited in the crust, it can undergo ohmic decay (Srinivasan et al 1990). As pointed out by Srinivasan et al (1990), a neutron star in a close binary system is spun down to a very long period (several hundred sec) in the wind-

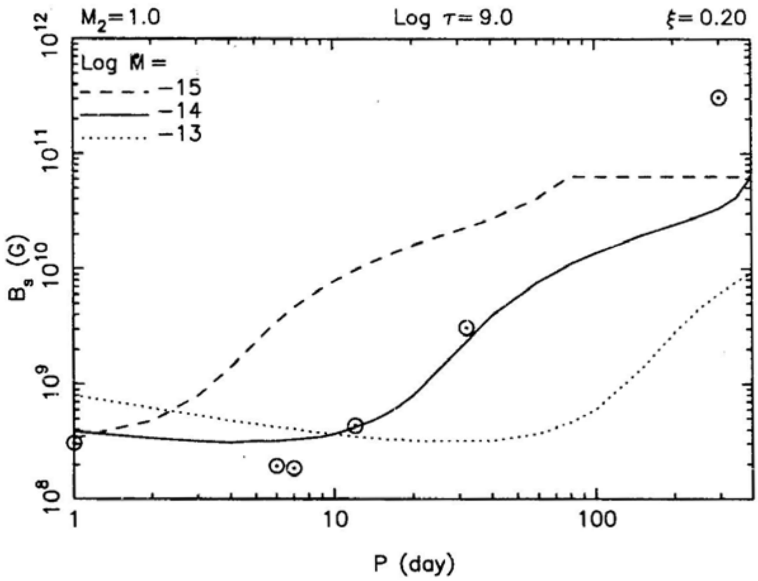

Figure 3: The final field strengths of the neutron stars in wide low-mass binaries as a function of the initial orbital period, according to the spindown-induced flux expulsion model. Results for three different mass loss rates of the secondary have been shown. The circles represent observed binary radio pulsars that are descendants of wide low-mass binaries, for which initial orbital periods can be estimated. See the caption of fig. 2 for explanation of legends. From Jahan Miri and Bhattacharya (1994).

interaction phase preceding the Roche Lobe overflow. Major flux expulsion from the superconducting interior takes place during this phase, and the expelled field eventually undergoes ohmic decay. It is to be noted that Ding et al (1993) obtained similar flux expulsion by dipole torques on isolated neutron stars, assuming the initial spin period of the neutron star to be $\lesssim 1$ ms. It is very doubtful, however, whether in the initial stages of the neutron star evolution, when the neutron star is very hot, the vortex-coupled flux movement can occur as effectively as Ding et al (1993) assume (Bhattacharya 1994). In addition, it is not at all clear whether many neutron stars are in fact born with such short spin periods. Indications to the contrary have been obtained in many statistical analyses (Vivekanand and Narayan 1983, Srinivasan et al 1984, Stokes et al 1986, Chevalier and Emmering 1986, Narayan 1987, Narayan and Ostriker 1990). In our view, field reduction by more than a factor of 5–10 can only be obtained by spindown due to interaction with a binary companion.

Spin-down to long periods due to interaction with the companion's stellar wind is indeed seen in massive X-ray binaries, where neutron star periods as long as 835 s have been observed (Nagase 1989). Since these objects show X-ray pulsations, it is clear, however, that their surface magnetic fields are not yet very low. This indicates that if spindown-induced flux expulsion is operative, then the field takes a considerable time to decay after the expulsion. This is only to be expected, since the conductivity of the inner crust is likely to be rather large. On the other hand, the recycled pulsars with the lowest magnetic fields, namely the millisecond pulsars, are believed to have descended from low-mass X-ray binaries, systems in which the wind accretion phase has never been observed. Could neutron stars in LMXBs have spun down to sufficiently long periods to explain the present field strengths of millisecond pulsars?

To address this issue, Jahan Miri and Bhattacharya (1994) consider coupled spin and magnetic field evolution of neutron stars in wide low-mass binary systems for a variety of assumed ohmic decay time scales of the expelled flux. The evolutionary calculations pertain to the main sequence phase of the secondary, during which the binary is detached. The mass of the secondary is assumed to be $1M_\odot$, and its wind rate is assumed to lie between 10^{-16} to 10^{-13} $M_\odot$/yr. The neutron star goes through, successively, the dipole, ejector and accretor phases (Davis and Pringle 1981). In the dipole phase the wind matter is unable to penetrate the magnetosphere and the spin-down occurs as in an isolated neutron star. In the ejector phase the wind matter interacts with the magnetosphere of the neutron star, extracting angular momentum and causing rapid spin-down. This also causes most of the flux expulsion from the core. As this expelled flux undergoes ohmic dissipation, causing the surface magnetic field to drop, wind matter begins to accrete on the neutron star surface and causes a slow spin-up. Once the spin-down phase is over, no further magnetic flux is expelled, and since new vortices are now introduced into the core the remaining flux is trapped for ever.

Fig. 2 demonstrates the typical evolution of one such system: the evolution of the spin period P_s, core magnetic field B_c and the surface field B_a as a function of time are shown. From the model computations for many such systems with a wide variety of initial conditions, it is found that to obtain final field strengths as low as ~ 10^8 G, an ohmic decay time scale in the range $10^{8.5}$–$10^{9.5}$ yr is required. For such values of ohmic times, these computations also find a definite correlation between the initial orbital period of the system and the final long-lived component of the surface field, which follow a trend very similar to that observed (fig. 3).

This work also finds that the transport of flux across the crust-core boundary plays a significant role in determining the final surface field strengths of neutron stars. The results quoted in the previous paragraph correspond to the case when flux moves across the interface without any hindrance, i.e. the flux expulsion occurs instantaneously in response to an increase in the spin period. It has, however, been pointed out by Jones (1987) that once the flux density in the solid crust reaches a value close to the lower critical field of the proton superconductor, further transport of flux across the boundary may be hindered, and a layer of high fluxoid density may build up just below the border. From then on flux would be released into the crust in the same time scale in which flux transport occurs in the solid – by ohmic diffusion, Hall transport or plastic flow. If the time scale for flux release is assumed to be that of the ohmic diffusion in the crust, then to explain observations the required ohmic time scales would be an order of magnitude less than those obtained for free flux flow (Jahan Miri and Bhattacharya 1994).

Ohmic time scales of order 10^8–10^9 yr are, however, much shorter than that computed for pure matter in the inner crust (Sang and Chanmugam 1987). But

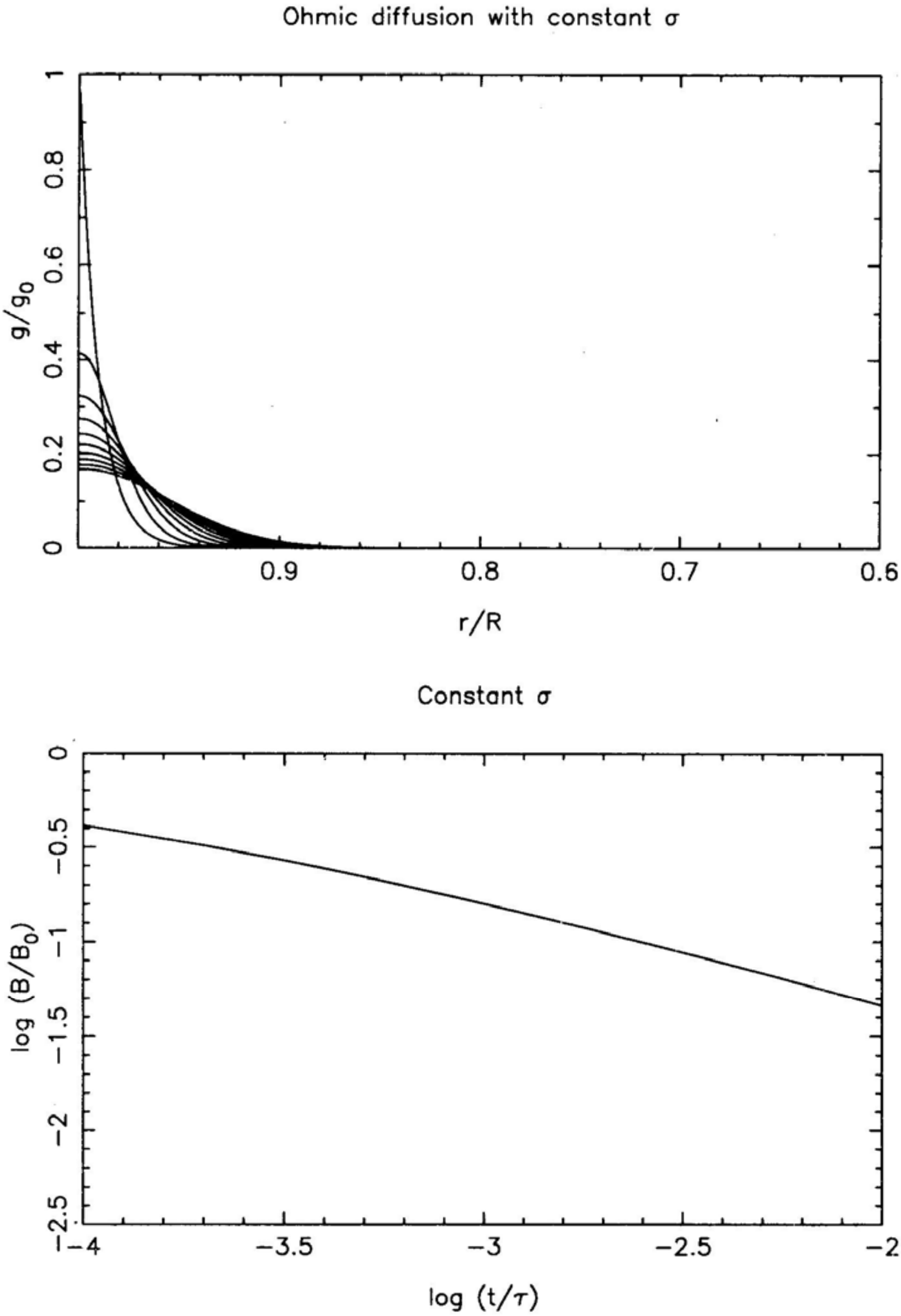

Figure 4: Ohmic diffusion of crustal magnetic field, assuming a constant electrical conductivity in the crust. The upper panel shows the evolution of the *g*-profile and the bottom panel the evolution of the field strength at the surface. See text for details.

it has been shown that even a small amount of impurities and dislocations can drastically reduce the ohmic time scale (Yakovlev and Urpin 1980, Urpin and Muslimov 1992). For the impurity parameter Q in the range 0.1–0.01 ($Q \equiv \{\Sigma_k \; n_k(Z - Z_k)^2\}/n_i$, where the dominant background ion species has density n_i and charge Z, and n_k, Z_k are the density and charge of the k-th interloper species), a range usually considered reasonable in the literature (e.g. Urpin and Muslimov 1992), computations show that the ohmic dissipation time of the expelled flux indeed lies in the range 10^8–10^9 yr (B. Datta and D. Bhattacharya, in preparation). Furthermore, the expelled field may undergo a turbulent cascade, reducing the scale length and hence the ohmic time (Goldreich and Reisenegger 1992).

4.2 *Ohmic evolution of crustal magnetic fields*

We shall now turn to the discussion of magnetic fields which are initially confined entirely to the crust. Most studies of this nature assume the initial field to be resident in the very outer layers of the crust, at densities below that of the neutron drip (i.e. 4×10^{11} g cm^{-3}) (cf. Urpin et al 1986). Ohmic evolution of this field is then computed as follows. The field is assumed to be dipolar, and to treat this a vector potential $\vec{A} = (0, 0, A_\phi)$ is introduced, with the form $A_\phi = g(r/R, t) \sin \theta / r$, where (r, θ, ϕ) are spherical polar coordinates with origin at the centre of the star, and R is the stellar radius. The field components can then be expressed in terms of the quantity $g(r/R, t)$ as

$$B_r = \frac{2g}{r^2}\cos\theta, \quad B_\theta = -\frac{\sin\theta}{r}\frac{\partial g}{\partial r}$$

The maximum field strength at the stellar surface is the polar value of B_r:

$$B_s(t) = 2g(1,t)/R^2$$

Using this description of the field, the equation for ohmic diffusion, namely,

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left(\frac{c^2}{4\pi\sigma}\nabla \times \vec{B}\right)$$

can be written as

$$\frac{\partial g}{\partial t} = \frac{c^2}{4\pi\sigma R^2}\left(\frac{\partial^2 g}{\partial x^2} - \frac{2g}{x^2}\right)$$

where $x = r/R$. In the above $\sigma(r, t)$)is the electrical conductivity. Following the ohmic evolution then just becomes a matter of solving the above one-dimensional second order partial differential equation, with the boundary conditions

$$\frac{\partial g}{\partial x} + g = 0 \quad \text{at } x = 1$$ (condition for dipole configuration),

and

$g = 0$ at $x = x_c$, below which the field is assumed not to penetrate

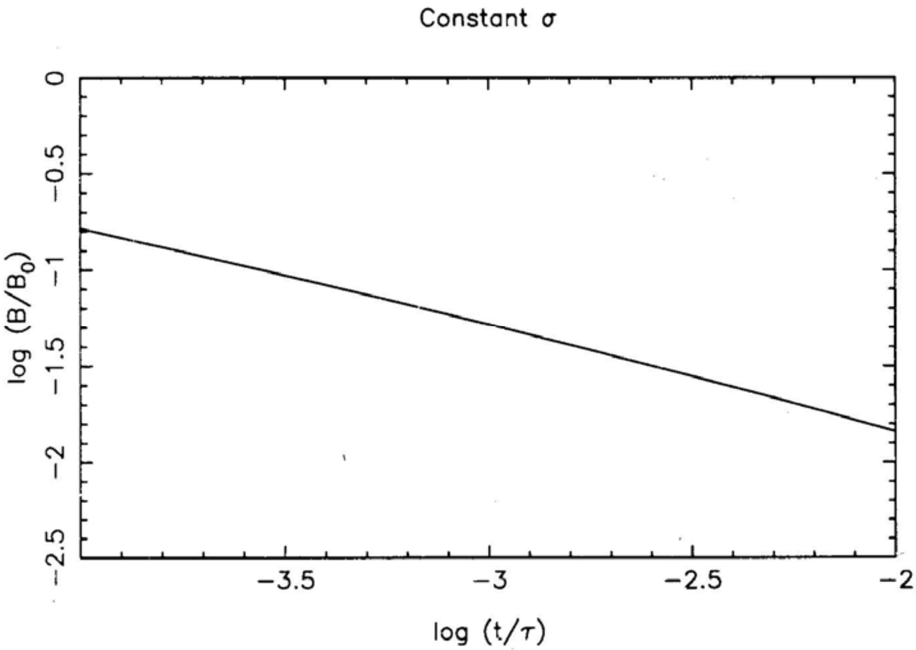

Figure 5; Evolution of the surface field strength if the initial g-distribution is assumed to be narrower by a factor of $\sqrt{10}$ compared to that in fig. 4.

(Wendell et al 1987, Sang and Chanmugam 1987, Urpin and Muslimov 1992). Two choices of x_c have been commonly used: zero, and that at the bottom of the crust. For fields initially confined to the outer crust, and a superconducting interior, the latter is possibly a better choice.

Clearly, two major parameters determine the ohmic evolution of the crustal field. One is the electrical conductivity, which is a function of the density, temperature and impurity concentration in the stellar interior, and since the stellar temperature is a function of time, the conductivity also acquires an implicit time dependence. The second is the scale length of the initial field distribution. The narrower the distribution, the faster is the decay.

In order to visualise the general trends in the basic evolution, we have constructed a series of evolutionary models with the electrical conductivity assumed to be *constant* from $x = x_c$ to $x = 1$, and infinite for $x < x_c$. The conductivity can then be absorbed into a time scale $\tau \equiv c^2/4\pi R^2\sigma$, all times be rescaled into those in units of τ, and computations restricted to $x > x_c$. Fig. 4 shows the evolution under such assumptions, with x_c (arbitrarily) set to 0.6. The initial g distribution is taken to be an exponential (the topmost curve in the upper panel) with a scale length $\Delta x = 0.01$. The top panel shows the evolution of the g-profile, in steps of 10^{-4} in t/τ, for the first 10 steps. The g-profile is seen to evolve towards wider and wider gaussians, a characteristic of the diffusion process. The bottom panel

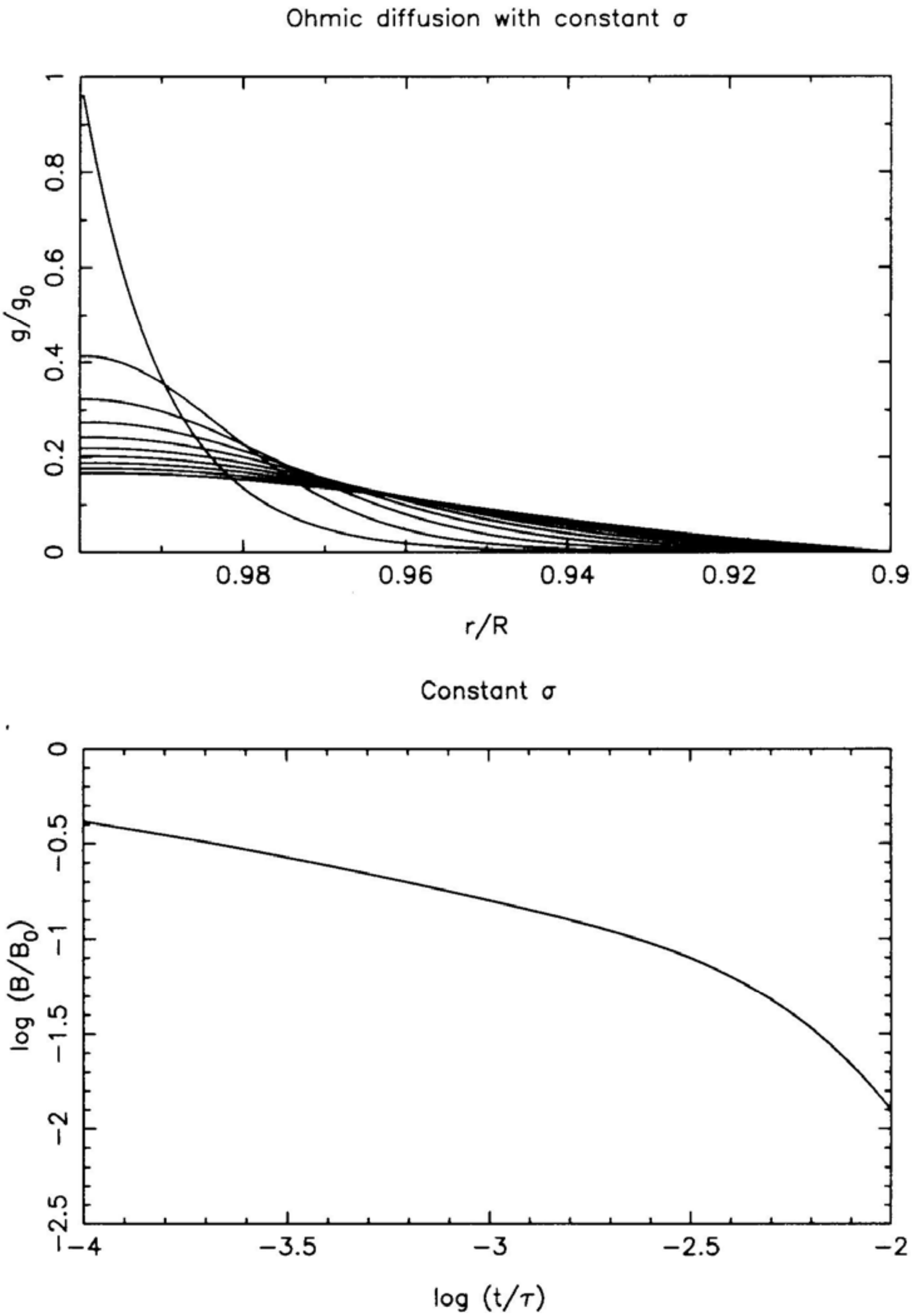

Figure 6: Same as fig. 4, but with the inner boundary set to $0.9R$ instead of $0.6R$.

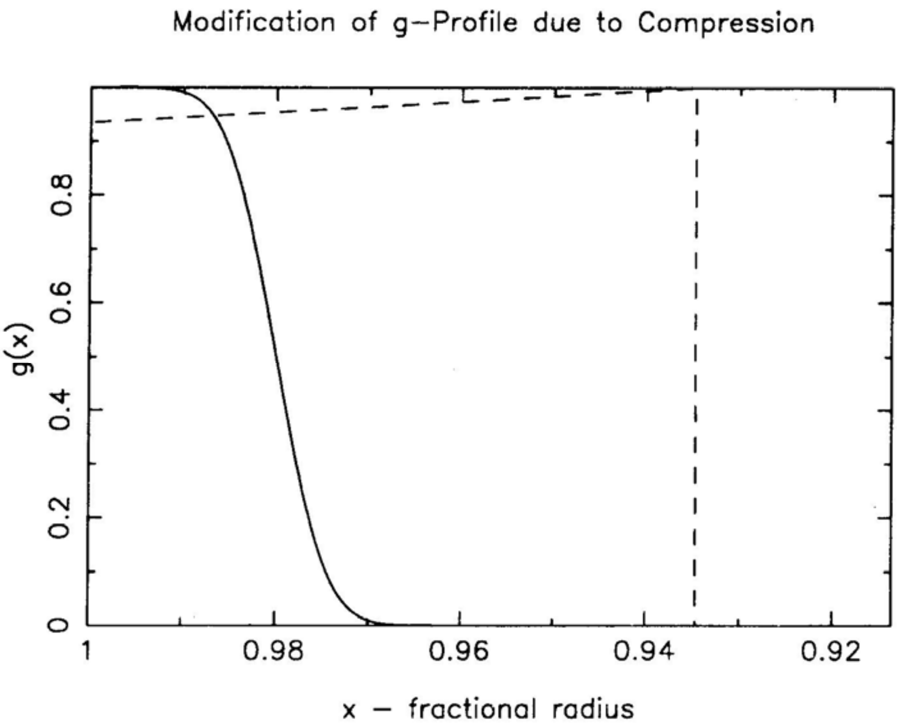

Figure 7: Modification of *g*-profile due to mass accretion on the surface of the neutron star. Solid line shows the initial profile, and the dashed line that after the accretion of $10^{-2}\,M_\odot$ of matter on a $1{\cdot}4M_\odot$ neutron star. No ohmic diffusion is assumed.

shows the evolution of the surface field strength. As can be seen, the evolution of the surface field strength is very close to a power law, a feature consistently obtained in late-time evolution of this kind of field in more realistic computations (e.g. Urpin and Muslimov 1992). In fig. 5 is shown a similar evolution, with all parameters other than the scale length of the original field kept the same as for fig. 4. The scale length has been reduced by a factor $\sqrt{10}$. The power-law nature of the evolution is seen again, but clearly the amount of decay at a given time is larger, by about the same factor by which the scale length has been reduced. Moreover, both in fig. 4 (bottom) and fig. 5 the power law index is close to –1/2, so the time required for the field to decay down to a given fraction of its original strength has been reduced by the square of the length scale reduction factor.

Why does the process of ohmic decay, which is commonly believed to behave exponentially, show a power-law behaviour in this case? It has been argued that the power-law arises due to the diffusion of the field into regions of higher conductivity (greater depth), which slows down the decay (Sang and Chanmugam 1987, Urpin and Muslimov 1992). The results presented above demonstrate that this is in fact not the major reason, for the power-law behaviour shows up even when the conductivity is assumed to be uniform. The real reason lies in the fact that

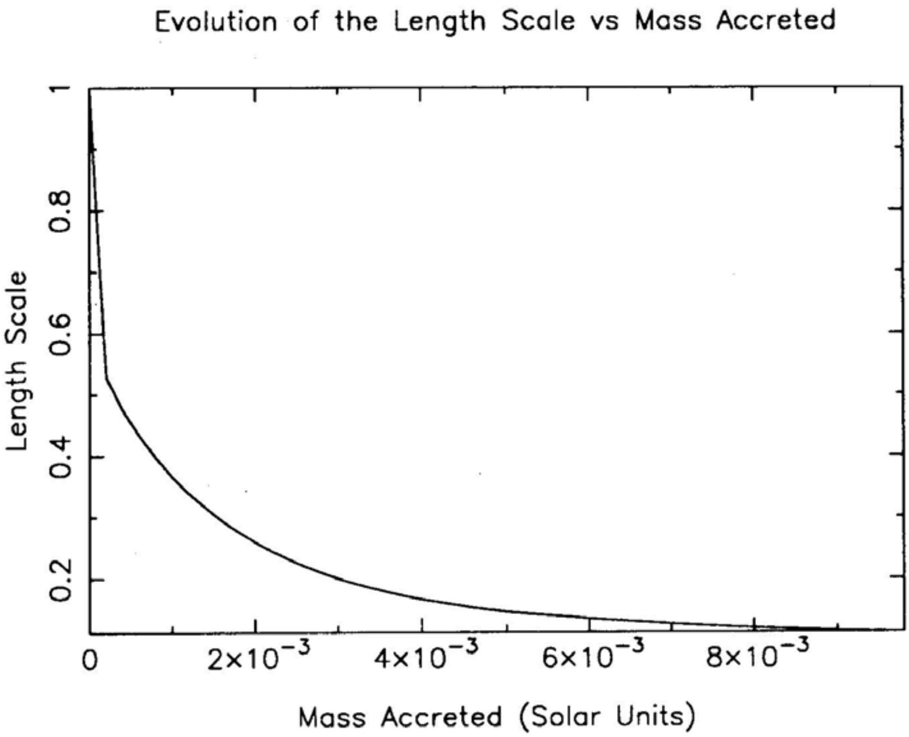

Figure 8: The evolution of the scale length of the *g*-distribution as a function of the accreted mass.

the original field occupies a very small fraction of the space in which it can later diffuse into. Described in fourier space, the original field distribution has a large amount of power in components of high order. Components of each order decay exponentially with a time scale appropriate for that order. Ohmic decay rate of the high-order components is much larger than that of components of lower order. As time progresses, the population of high-order components is depleted (the *g*-profile widening as a result), and the relevant decay time increases, resulting in a power-law behaviour. Once the field distribution occupies nearly all of the available space, the behaviour turns into an exponential, since no further reduction in the order number of the fourier components is possible. This transition can be easily seen in the evolution of an original *g*-distribution identical to that in fig. 4, but with x_c = 0.9, below which the field is now not allowed to diffuse. The evolution of the surface field strength in this case in shown in fig. 6, where the later part of the decay is very nearly an exponential.

The above discussion clearly demonstrates the very important role played by the scale length of the magnetic field distribution in determining the decay rate. It is to be noted at this point that mass accretion on the surface of the neutron star can drastically modify the scale length of the *g*-distribution. If the original profile is confined to the outer regions of the crust, the weight of the accreted matter pushes this region into those of much higher density, compressing the whole layer in the process, the radial extent occupied by this slice of matter is thus enormously reduced, and so is the scale length of the *g*-distribution frozen into this. Fig. 7 compares the *g*-profile before (solid line) and after (dashed line) the accretion of $10^{-2}\,M_\odot$ on a neutron star of mass $1{\cdot}4M_\odot$ constructed with the equation of state of Wiringa, Fiks and Fabrocini (1988). It is clearly seen that the final profile is much sharper than the initial one. Fig. 8 shows the evolution of the scale length as a function of the mass accreted. No ohmic diffusion *during* the accretion process is assumed, and the accreted mass is assumed to settle uniformly over the neutron star surface. This huge compression in the length scale during accretion is likely to lead to a mass accretion-induced decay of the magnetic field, similar to the empirical suggestions by Taam and van den Heuvel (1986) and Shibazaki et al (1989). In reality the effect of compression will be reduced by the current distribution moving to regions of higher density and hence higher conductivity. However, the accretion process is also likely to raise the temperature of the crust and reduce the electrical conductivity as a result. Investigation of the evolution taking into account all these aspects is currently in progress (Geppert and Urpin 1994; S. Konar and D. Bha ttacharya, in preparation).

5. Summary

To summarize, it appears fr om recent observations and analyses of pulsar data that the decay of the magnetic field of a neutron star may be closely linked to the interaction of the star with a binary companion. Different physical models have been suggested for such evolution. If the original magnetic field resides in the core, the model of pinning between fluxoids in superconducting protons and vortices in the neutron superfluid predicts that during the interaction with the companion's stellar wind, the neutron star would spin down to long periods, expelling much of the core flux into the bottom of the crust. Good match with the observations can be obtained in this model if this expelled magnetic flux undergoes ohmic decay in a time scale of order 10^8–10^9 yr. Calculations of ohmic evolution of the expelled flux shows that time scales in this range can be easily obtained, for very reasonable impurity concentrations in the inner crust. On the other hand, if the original magnetic field resides entirely in the crust, and not decay appreciably in an isolated neutron star, then accretion of matter on the neutron star can vastly hasten the ohmic decay, due to the reduction of the scale length of the original field distribution caused by compression, and the reduction in conductivity resulting from heating. Other models of accretion-induced field reduction, involving inverse thermoelectric battery and reconnections caused by hydrodynamic flow, have also been suggested in the literature.

Acknowledgements

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