Mon. Not. R. Astron. Soc. **284,** 311–317 (1997)

Magnetic field evolution of accreting neutron stars

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Accepted 1996 July 30. Received 1996 July 26; in original form 1996 March 29

ABSTRACT

Observations suggest a connection between the low magnetic fields of binary and millisecond pulsars and their being processed in binary systems, indicating accretion-induced field decay in such cases. A possible mechanism is that of rapid ohmic decay in the accretion-heated crust. The effect of accretion on purely crustal fields, for which the current loops are completely confined within the solid crust, is two-fold. On the one hand the heating reduces the electrical conductivity and consequently the ohmic decay time-scale, inducing a faster decay of the field. At the same time the material movement, caused by the deposition of matter on top of the crust, pushes the original current-carrying layers into deeper and denser regions where the higher conductivity slows the decay down. This results in a competition between these two opposing processes. The mass of the crust of a neutron star changes very little with a change in the total mass; accretion therefore implies assimilation of the original crust into the superconducting core. When the original current-carrying regions undergo such assimilation, further decay is stopped altogether. We perform model evolutionary calculations for a range of values of the accretion rate and the crustal temperature. We find that in all cases an initial phase of *rapid decay* is followed by a slow-down and finally a *freezing* of the surface field. The pre-accretion phase of field decay in the effectively isolated neutron star plays a significant role. In this phase the currents diffuse down through the whole of the crust by pure ohmic dissipation, and the longer it lasts the deeper the currents penetrate. If prior to the accretion phase the currents have already penetrated to the regions of high density and hence high conductivity, the effect of crustal heating is not as dramatic.

Key words: magnetic fields – binaries: general – stars: neutron – pulsars: general.

1 INTRODUCTION

Recent observations of pulsars and their statistical analyses appear to indicate that:

(i) isolated pulsars with high magnetic fields ($\sim 10^{11}-10^{13}$ G) do not undergo any significant field decay during their lifetimes (Bhattacharya et al. 1992; Wakatsuki et al. 1992; Lorimer 1994);

(ii) binary pulsars as well as millisecond and globular cluster pulsars, which almost always have a history of being a member of a binary, possess very low field strengths, down to $\sim 10^8$ G; and

(iii) most of these low-field pulsars are also quite old (age $\sim 10^9$ yr), which implies that their field must be stable over such periods, i.e., the field is not undergoing decay any more (Bhattacharya & Srinivasan 1986; Kulkarni 1986; van den Heuvel, van Paradijs & Taam 1986; Verbunt, Wijers & Burm 1990).

In order to understand the above facts, attempts have been made to relate the field decay to the binary history of the star. There are two classes of models which have been explored in this regard, one that relates the magnetic field evolution to the spin evolution of the star and the other attributing the field evolution to direct effects of mass accretion [see Ruderman (1995) and Bhattacharya (1995) for detailed reviews].

The former class of models involves the interpinning of the Abrikosov fluxoids (of the superconducting protons) and the Onsager–Feynman vortices (of the superfluid neutrons) in the core (Srinivasan et al. 1990; Ruderman 1991a). This class also includes the models involving the plate tectonics of the neutron star crust (Ruderman 1991b,c). Srinivasan et al. (1990) pointed out that neutron stars interacting with the wind of the companion would experience major spindown, causing the superconducting core to expel the magnetic flux, which would then undergo ohmic decay in the crust. Jahan Miri & Bhattacharya (1994) have modelled this coupled evolution of spin and magnetic field in wide low-mass X-ray binaries, and obtained satisfactory agreement with the observations. Ruderman (1991b,c), on the other hand, suggests a coupling between the spin and the magnetic evolution of the star via crustal plate tectonics – torques acting on the star cause crustal plates, and the magnetic poles anchored in them, to migrate, resulting in major changes of the effective dipole moment.

In this paper we explore models in the second category, namely those that attribute the field decay to direct effects of accretion.

Previous work by Bisnovatyi-Kogan & Komberg (1974) and Taam & van den Heuvel (1986) have suggested that accreted matter might screen the pre-existing field. Computations by Romani (1990) indicate that hydrodynamic flows may bury the pre-existing field, reducing the strength at the surface. In the present paper we look at a somewhat different mechanism for the accretion-induced field decay. Here the decay takes place principally as a result of rapid dissipation of currents due to the elevation of the crustal temperatures, similar to the situation explored by Geppert & Urpin (1994) and Urpin & Geppert (1995, 1996).

We assume that the current loops producing the neutron star magnetic field are confined entirely within the crust to start with. This situation is the likely result of the generation of the magnetic field due to thermomagnetic instabilities after the birth of the star (Blandford, Applegate & Hernquist 1983; Urpin, Levshakov & Yakovlev 1986). If the initial field resides mainly in the superconducting core then our scenario will apply only after most of this flux has been expelled into the crust.

The crustal field undergoes ohmic diffusion due to the finite electrical conductivity of the crustal lattice, but the time-scale of such decay is very long under ordinary conditions (Sang & Chanmugam 1987; Urpin & Muslimov 1992). The situation changes significantly when accretion is turned on. The heating of the crust reduces the electrical conductivity by several orders of magnitude, thereby reducing the ohmic decay time-scale. However, there is also an additional effect that acts towards stabilizing the field. As the mass increases, a neutron star becomes more and more compact and the mass of the crust actually decreases by a small amount. So the newly accreted material forms the crust and the original crustal material gets continually assimilated into the superconducting core below. The original current-carrying layers are thus pushed into deeper and more dense regions as accretion proceeds. The higher conductivity of the denser regions will progressively slow down the decay, until the current loops are completely inside the superconducting region where any further decay is prevented.

We investigate the above-mentioned mechanism of field decay in this paper and try to understand its importance in real systems. The organization of the paper is as follows. In Section 2 we outline the physics of the mechanism and provide a description of the model adopted for our calculations. Section 3 gives the relevant details of the numerical computation. In Section 4 we discuss the relevance of the results obtained from our model calculations in the real cases of accreting neutron stars, and we draw the final conclusions in Section 5.

2 PHYSICS OF THE MECHANISM

The evolution of the crustal field as a result of ohmic diffusion and material motion has been discussed by a number of authors (Wendell, van Horn & Sargent 1983; Sang & Chanmugam 1987; Geppert & Urpin 1994), and essentially concerns the solution of the following equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \times \nabla \times \boldsymbol{B} \right), \tag{1}$$

where $\boldsymbol{V}$ is the velocity of material movement and σ is the electrical conductivity of the medium.

As in previous studies we solve this equation by introducing the vector potential $\boldsymbol{A} = (0, 0, A_\phi)$, where $A_\phi = g(r,t)\sin\theta/r$; (r, θ, ϕ) being the spherical polar coordinates. Introduction of this function in equation (1) leads to

$$\frac{\partial g(r,t)}{\partial t} = V(r)\frac{\partial g(r,t)}{\partial r} + \frac{c^2}{4\pi\sigma}\left[\frac{\partial^2 g(r,t)}{\partial r^2} - \frac{2g(r,t)}{r^2}\right]. \tag{2}$$

The radius and the crustal mass of a neutron star remain effectively constant for the maximum amount of accreted masses considered in this paper, and the corresponding change in the crustal density profile is negligible. We therefore take the mass flux to be the same throughout the crust, equal to its value at the surface. Assuming the mass flow to be spherically symmetric in the crustal layers of interest, one obtains the velocity of material movement:

$$V(r) = \frac{\dot{M}}{4\pi r^2 \rho(r)}, \tag{3}$$

where $\dot{M}$ is the rate of mass accretion and $\rho(r)$ is the density as a function of radius r. The results in this paper will be based on numerical solutions of the equations (1) and (2) above.

2.1 Ohmic diffusion

It is clear from the evolution equation that the rate of ohmic diffusion is determined mainly by the electrical conductivity of the crust. As conductivity is a steeply increasing function of density and since the density in the crust spans eight orders of magnitude, the conductivity changes sharply as a function of depth from the neutron star surface. Thus the deeper the location of the current distribution, the slower the decay.

Another important factor in determining the conductivity is the temperature of the crust. In the absence of impurities the scattering of crustal electrons comes entirely from the phonons in the lattice (Yakovlev & Urpin 1980) and the number density of phonons increases steeply with temperature. The cooling of an isolated neutron star brings the surface temperature down to ~$10^{4.5}$ K in about 10^7 yr (van Riper 1991) with an attendant interior temperature of the nearly isothermal core of the order of 10^7 K. Once this star begins to accrete, the surface temperature is raised and within a short time (~10^5 yr) almost the entire crust is heated to a constant temperature of the order of $10^{7.5} - 10^{8.5}$ K (Miralda-Escudé, Haensel & Paczyński 1990).

A third parameter that should be considered in determining conductivity is the impurity concentration. The effect of impurities on the conductivity is usually parametrized by a quantity Q, defined as $Q = \frac{1}{n}\sum_i n_i (Z - Z_i)^2$, where n is the total ion density, n_i is the density of impurity species i with charge Z_i, and Z is the ionic charge in the pure lattice (Yakovlev & Urpin 1980). It has been assumed in the literature that Q lies in the range 0.01–0.1. The effect of impurities is most important at lower temperatures and higher densities. Therefore the field evolution does not show any significant difference for different impurity concentration in an accretion-heated crust, which is the reason that we restrict our computations to the $Q = 0.0$ case. However, the impurity concentration would still play an important role in the pre-accretion phase of isolated decay where the crustal temperatures could be quite low.

2.2 Accretion and material transport

In a neutron star, for a given equation of state, the mass of the crust is uniquely determined by the total mass of the star. In addition, this crustal mass remains effectively constant for accreted masses of the order of 0.1 $M_\odot$ with a slight decrease as the total mass increases; for example, for the equation of state that we have used (see Section 3 for details), the accretion of 0.1 $M_\odot$ on to the star causes a change in the crustal mass of only 0.004 $M_\odot$. As a result, accretion causes continuous assimilation of material from the bottom of the crust into the core. At the same time the upper layers of the original crust are pushed to deeper and denser regions, leading to extreme squeezing of this material. This also causes the current distribution embedded in this material to be sharpened, reducing the effective length-scale of the system.

The result of accretion on the magnetic field evolution therefore manifests itself as a combination of three effects: transport of the current distribution to regions of higher density and hence higher conductivity, reduction of conductivity due to heating, and reduction of the effective length-scale of the current distribution [see Bhattacharya (1995) for a detailed discussion]. We find that the overall effect turns out to be a rapid initial decay followed by a levelling off when much of the original crust has been assimilated into the superconducting interior, freezing the currents there. Following Baym, Pethick & Pines (1969) we assume that the newly formed superconducting material retains the magnetic flux through it in the form of Abrikosov fluxoids rather than expelling it through the Meissner effect.

3 COMPUTATIONS

The aim of our computations is to solve equation (2) to obtain $g(r, t)$ using the following boundary conditions valid for all times (see, e.g., Geppert & Urpin 1994):

$$\frac{\partial g(r,t)}{\partial r}\Big|_{r=R} + \frac{g(R,t)}{R} = 0, \tag{4}$$

$$g(r_{co}, t) = 0, \tag{5}$$

where R is the radius of the star and r_{co} is that radius to which the original boundary between the core and the crust is pushed, due to accretion, at any point of time. The first condition matches the interior field to an external dipole configuration. The second condition indicates that, as accretion proceeds, along with the crustal material the frozen-in flux moves inside the core. To simulate an effectively infinite conductivity in the region between the bottom of the crust and the original boundary between the crust and the core, we set $\sigma \sim 10^{50}\ \mathrm{s}^{-1}$ in this region. As mentioned before, we take into account the combined effects of accretion-driven material motion and ohmic diffusion. We construct the density profile of the neutron star in question using the equation of state of Wiringa, Fiks & Fabrocini (1988) matched to Negele & Vautherin (1973) and Baym, Pethick & Sutherland (1971) for an assumed mass of 1.4 $M_\odot$. This star has a total crustal mass of 0.044 $M_\odot$ and we restrict our evolutionary calculations to a maximum net accretion of this additional amount on to the star. The change in the crustal density profile resulting from this additional mass is negligible. Hence we work with an invariant crustal density profile throughout our calculation.

We assume that the matter settling on to the star does so uniformly across the entire surface. This allows us to use the expression of $V(r)$ as in equation (3). When the surface magnetic field is strong this is a poor approximation very close to the surface. However, in deeper layers ($\rho \gtrsim 10^8\ \mathrm{g\ cm^{-3}}$) with which we are mainly concerned, the material motion is essentially dictated by the added weight and is going to be more or less isotropic.

We further assume that the incoming matter fully threads the existing magnetic field before settling on to the surface: in other words we allow for no reduction of the external magnetic field arising out of diamagnetic screening by the incoming material. While this may not be strictly true in reality, we adopt this scheme to ensure that the effects under investigation in this paper, namely diffusion and convection, do not get masked by other effects such as screening. In any case the degree to which screening may operate in the first place is unclear, as the resistivity of the incoming plasma is hard to calculate. Further, as has been shown by Young & Chanmugam (1995), the magnetic field once screened by diamagnetic effects does reappear in time.

We assume that during the accretion phase the temperature of the crust is uniform and constant in time. This ignores an initial short phase in which both the rate of accretion and the temperature of the crust show time evolution. The rate of accretion stabilizes in a few thousand years (Savonije 1978) and the temperature within 10^5 yr (Miralda-Escudé et al. 1990). Computations by Urpin & Geppert (1996) show that the decay during this initial phase is insignificant. The temperature that the crust will finally attain in the steady phase has been computed by Fujimoto et al. (1984), Miralda-Escudé et al. (1990) and Zdunik et al. (1992). However, these computations are restricted to a limited range of mass accretion, and also do not yield the same crustal temperature under similar conditions. The results obtained by Zdunik et al. (1992) for the crustal temperatures for a given accretion rate in the range $10^{-15} < \dot{M} < 2 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ could be fitted to the following formula:

$$\log T = 0.397 \log \dot{M} + 12.35. \tag{6}$$

However, extrapolation of this fit to higher rates of accretion gives extremely high temperatures, which would not be sustainable for any reasonable period due to rapid cooling by neutrinos at those temperatures. We have therefore restricted our computations to a maximum accretion rate of $10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$, and, for $\dot{M}$ in the range 10^{-10}–$10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$, we have explored a range of constant crustal temperatures between 10^8 and $10^{8.75}$ K.

The conductivity of the solid crust is given by

$$\frac{1}{\sigma} = \frac{1}{\sigma_{ph}} + \frac{1}{\sigma_{imp}},$$

where σ_{ph} is the phonon scattering conductivity obtained from Itoh et al. (1984) as a function of density and the temperature; and σ_{imp} which is a function of density and the impurity parameter Q is taken from the expressions given by Yakovlev & Urpin (1980).

In a series of papers Geppert & Urpin (1994), Urpin & Geppert (1995, 1996) and Geppert, Urpin & Konenkov (1995) have considered evolution of crustal magnetic fields for accretion rates in the range 10^{-15}–$10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$. In this paper we too consider accretion rates covering much of the above range. The difference between our computations and those in the above papers lies in the range of total mass accretion. Our computations proceed to a maximum net accretion of $\sim 4 \times 10^{-2}\ M_\odot$, whereas the computations by other authors are restricted to that of the order of $10^{-3}\ M_\odot$. Our choice of the range of accretion rates also facilitates the comparison of our results with those available in the literature, over the range of overlap in the net mass accreted.

We solve equation (2) using a modified Crank–Nicholson scheme. Since the conductivity is a function of density and hence of radius, it has been neccessary to incorporate the space dependence of the conductivity in the standard Crank–Nicholson scheme of differencing. In addition, we also allow for a pre-accretion phase where the neutron star undergoes normal cooling. This introduces a time dependence in the temperature and hence in the diffusion constant as well. We introduce the convection term into the computation through upwind differencing and operator splitting of the full differential equation (Press et al. 1992).

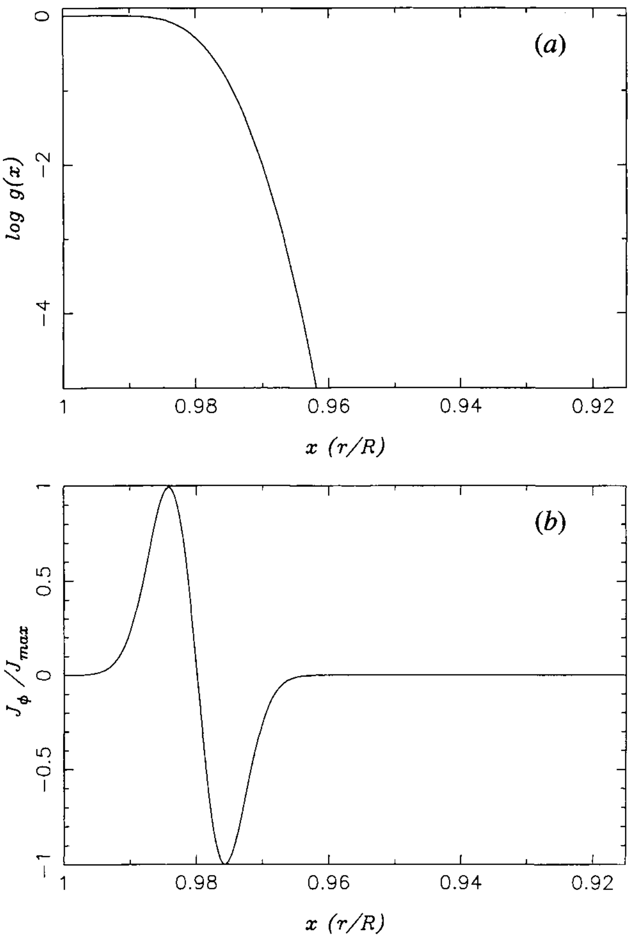

Figure 1. (a) The initial radial dependence of the g-profile centred at $x = 0.98$, with a width $\delta x = 0.006$; where x is the fractional radius r/R. (b) The initial radial dependence of the ϕ-component of the corresponding current configuration.

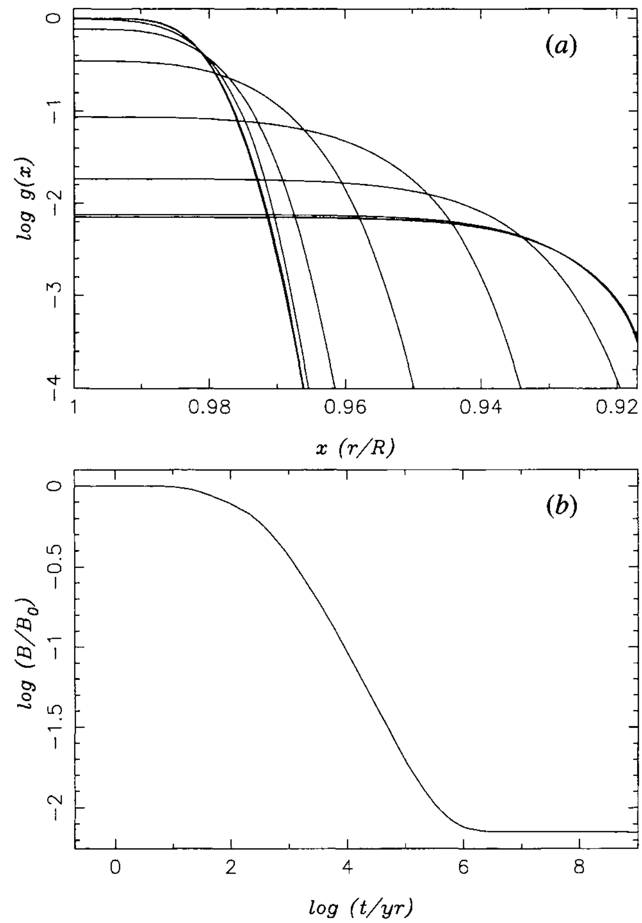

Figure 2. (a) Pure ohmic diffusion of the g-profile for $t \sim 10^9$ yr, centred at $\rho = 10^{11}$ g cm^{-3}, with $Q = 0.0$, in a neutron star with standard cooling. The curves shown at intermediate times correspond to $t = 10, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 10^8, 10^9$ yr (the last three are almost indistinguishable), respectively, with decreasing values at the surface ($x = 1$). (b) The corresponding evolution of the surface magnetic field.

4 RESULTS AND DISCUSSION

Our results are summarized in a series of figures, 1 to 7.

Fig. 1 shows the distribution of the g-function and the toroidal currents, assumed at the starting point of our evolution.

Field decay due to pure diffusion in an isolated neutron star is shown in Fig. 2. In computing this, neutron star cooling according to the results of van Riper (1991) for normal matter in a 1.4-M$_\odot$ Friedman & Pandharipande (1981) model star has been used. It should be noted that our adopted equation of state, namely that of Wiringa et al. (1988), is an updated version of the Friedman & Pandharipande equation of state with only minor differences. Among the published cooling curves this is the nearest to that appropriate to our adopted neutron star model. Computations similar to the one displayed in Fig. 2 have been made by Urpin & Muslimov (1992) and our result matches very closely with theirs.

Fig. 3 displays the result of the convection due to material movement alone. We obtain this by setting the conductivity σ to an artificially high value of 10^{50} s^{-1} in our code. It shows the migration of the g-profile to regions of higher density (and consequent sharpening of the profile). The field at the surface ($B_s = 2g\sin\theta/r^2$) remains constant under pure convection according to our assumptions.

Fig. 4 shows the results of the combined effects of convection and diffusion on the g-function, in other words the full evolution described by equation (2), for a particular combination of the accretion rate and the constant crustal temperature.

In Fig. 5 we display the evolution of the surface field for different values of $\dot{M}$, with temperatures obtained from equation (5) over its validity range, and for three different assumed temperatures at the highest accretion rate.

The following features emerge from the behaviour displayed in these figures.

(i) The general nature of the decay corresponds to an initial rapid phase exhibiting a power-law behaviour for the most part with an index ranging from 0.1 to 0.46 (i.e., $B \sim t^{-n}, 0.1 \lesssim n \lesssim 0.46$), followed by a short exponential phase and then a freezing, which stabilizes the surface field. This stability is the result of the entire current distribution, responsible for the field, being assimilated into the highly conducting core. According to our adopted scenario, the ohmic time-scale in the core is much longer than the Hubble time and hence the surface field at this stage will essentially be stable forever. We refer to this surface field as the *'residual field'*.

(ii) The duration of the exponential phase and consequently the value of the magnetic field at which freezing occurs are a strong

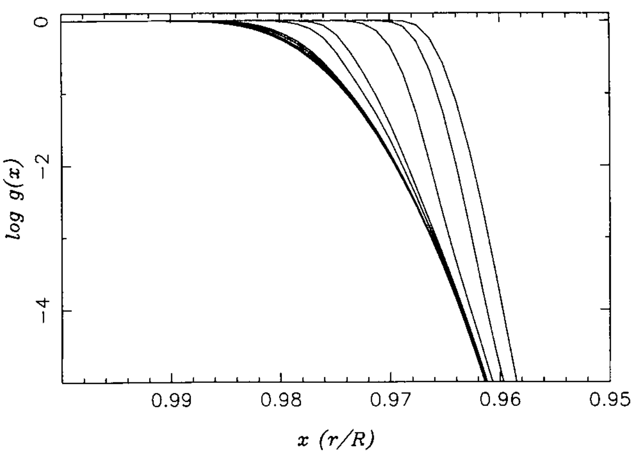

Figure 3. Convective transport of the g-profile over 10^9 yr with $\dot{M} = 10^{-13}\,\mathrm{M_\odot\,yr^{-1}}$; the surface field is constant by assumption. The curves shown at intermediate times correspond to $t = 10, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 10^8, 10^9$ yr (the first four are barely distinguishable), respectively, with the profiles progressively moving inwards.

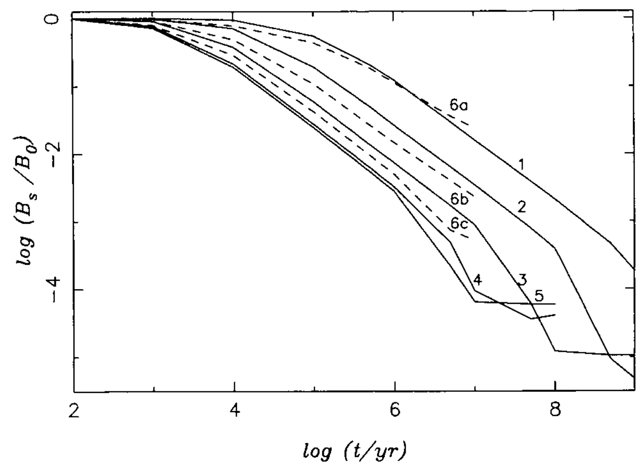

Figure 5. Evolution of the surface magnetic field for six values of accretion rate. The curves 1 to 5 correspond to $\dot{M} = 10^{-13}, 10^{-12}, 10^{-11}, 10^{-10}, 2.0 \times 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$ with the crustal temperatures obtained from equation (6). The dashed curves 6a, 6b and 6c correspond to $T = 10^{8.0}, 10^{8.25}$ and $10^{8.5}$ K respectively for an accretion rate of $\dot{M} = 10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$. All curves correspond to $Q = 0.0$, but are insensitive to the value of Q.

function of the accretion rate. The higher the accretion rate the sooner the freezing sets in, resulting in a higher value of the 'residual field'. This effect can be understood as follows. As explained by Bhattacharya (1995), the decay behaviour turns from a power law to an exponential, once the diffused g-distribution reaches nearly the bottom of the crust. The transition from there to the frozen state happens by further accretion of matter which pushes the crustal material into the core. The time required for this final transition is of course dependent on the accretion rate, and the higher the accretion rate the smaller it is. For a rate of accretion of $10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$, this exponential phase is nearly absent.

(iii) The dependence of the decay on the crustal temperature is as expected, namely the decay proceeds faster at higher temperature.

(iv) In Fig. 6 the evolution of the surface magnetic field as a function of total accreted mass has been plotted for different rates of accretion. Corresponding to a given accretion rate, the crustal temperature has been obtained from the formula fitted to the results of Zdunik et al. (1992). It is observed that the *freezing in* of the field occurs for large accreted mass for high rates of accretion. The high accretion rate also ensures quicker material transport to higher densities, causing the field strength to level off at a higher value. Another important point to note here is that, unlike what is assumed in heuristic evolutionary models (Taam & van den Heuvel 1986; Shibazaki et al. 1989; van den Heuvel & Bitzaraki 1995), the amount of field decay is dependent not only on the total mass accreted but also on the accretion rate itself.

(v) In practice a neutron star will often undergo a non-accreting phase of considerable duration before accretion can begin on its surface. During this initial phase its magnetic field will evolve as in an isolated neutron star, namely according to the evolution shown in Fig. 2. This has important physical consequences for the evolution in the accretion phase. The diffusion in the pre-accretion phase causes the currents already to penetrate to deeper

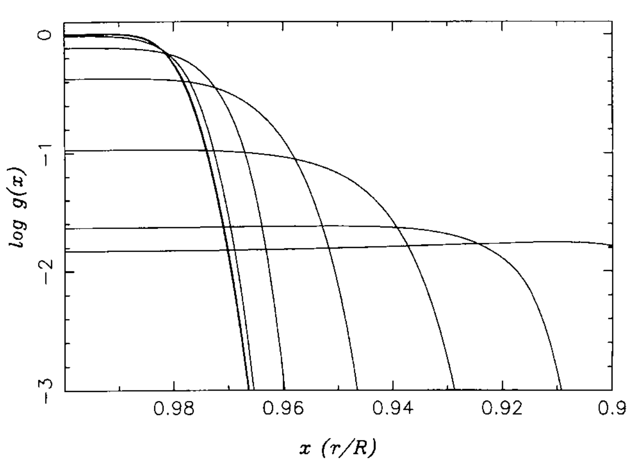

Figure 4. Evolution of the g-profile due to ohmic diffusion and convective transport, over a period of 10^6 yr for $\dot{M} = 10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$, $T = 10^{8.0}$ K and $Q = 0.0$. The curves shown at intermediate times correspond to $t = 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 4.0 \times 10^7$ yr, respectively, with decreasing values at the surface ($x = 1$).

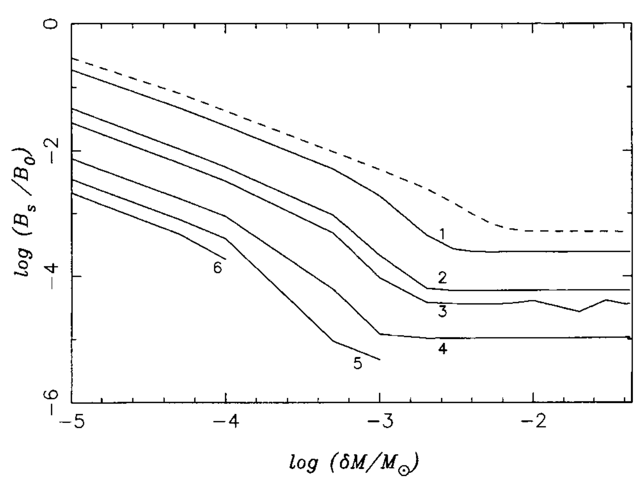

Figure 6. Evolution of the surface magnetic field as a function of total mass accreted. The curves 1 to 6 correspond to $\dot{M} = 10^{-9}, 2.0 \times 10^{-10}, 10^{-10}, 10^{-11}, 10^{-12}, 10^{-13}\,\mathrm{M_\odot\,yr^{-1}}$; the crustal temperatures are obtained from equation (6). The dashed curve corresponds to $\dot{M} = 10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$ and $T = 10^{8.5}$ K.

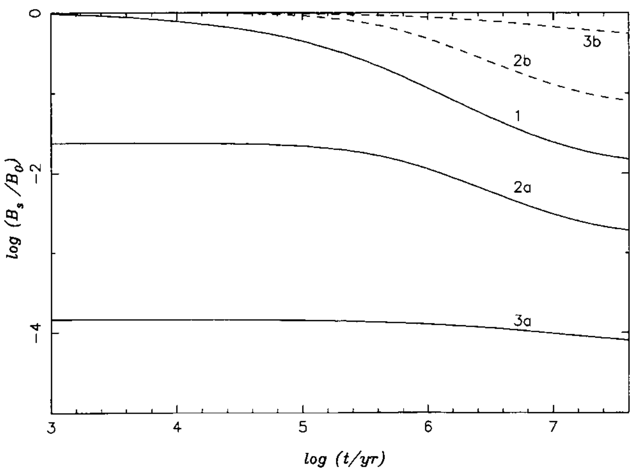

Figure 7. Evolution of the surface magnetic field (1) without any pre-accretion phase and (2 & 3) for such a phase lasting ~10^9 yr. In all cases $\dot{M} = 10^{-9}\,M_\odot\,yr^{-1}$ and $T = 10^{8.0}$ K. $Q = 0.0$ for curves 1, 2a, 2b and $Q = 0.1$ for 3a, 3b. In 2a and 3a the actual surface field has been plotted, whereas in 2b and 3b it has been scaled to the value of the field at the beginning of the accretion phase.

and denser regions of high conductivity. As a result the net decay achieved *during subsequent accretion* is small. Fig. 7 compares the evolution of the surface field without and with the pre-accretion phase lasting 10^9 yr. It should also be noted that, for accretion-induced field decay with an effectively isolated pre-accretion phase, the impurity concentration plays an important role too. Although the actual final field values obtained are small for large Q, the decay experienced in the accretion phase is significantly less in such cases and the '*freezing*' sets in much faster.

(vi) As mentioned before, the range of conditions explored by us overlap with those in the work of Urpin & Geppert (1995, 1996) and Geppert, Urpin & Konenkov (1995), and goes beyond. We have performed detailed comparisons of our results with theirs in the overlap range. The agreement in general is found to be excellent, giving us confidence in the validity of our approach.

To summarize, we have explored accretion-driven evolution of crustal magnetic fields over a range of conditions not previously attempted in the literature. The new behaviour revealed by these computations includes a near-exponential decay of the surface field after the initial power-law phase and, most importantly, an eventual freezing. The 'residual field' corresponding to this frozen state is a function of the accretion rate and the temperature during the evolution. It is interesting to note that for near-Eddington accretion rates, applicable to the Roche-lobe overflow phase in real binaries, the 'residual field' lies between 10^{-2} and 10^{-4} of the original value. So, if the neutron star originally started with a field strength of the order of 10^{12} G, this would mean a final post-accretion field strength of ~10^8–10^{10} G, exactly as observed in most recycled pulsars. Unfortunately, we have not been able to treat accretion rates equal to or larger than Eddington in the present work due to lack of knowledge about the crustal temperatures at those accretion rates. However, judging by the dependence of the behaviour on accretion rates, it appears that even somewhat higher post-accretion field strengths might be possible under such conditions. Recycled pulsars with the strongest magnetic fields, namely PSR 0820+02 and PSR 2303+46, have, according to evolutionary scenarios (see, e.g., Bhattacharya & van den Heuvel 1991), undergone super-Eddington mass transfers. Their field strengths would therefore be in agreement with the trend described above.

5 CONCLUSIONS

In this paper, we have explored the evolution of the crustal magnetic fields of accreting neutron stars. The combination of enhanced ohmic diffusion due to crustal heating and the transport of current-carrying layers to higher densities due to the accreted overburden causes the surface field strength to exhibit the following behaviour:

(i) an initial rapid decay (power-law behaviour followed by exponential behaviour) followed by a levelling off (freezing),

(ii) faster onset of freezing at higher crustal temperatures and at a lower final value of the surface field,

(iii) lower final fields for lower rates of accretion for the same net amount of accretion, and

(iv) the longer the duration of the pre-accretion phase the less the amount of field decay during the accretion phase.

ACKNOWLEDGMENTS

We thank V. A. Urpin and Ramesh Narayan for suggesting some interesting lines of investigation, and Rajaram Nityananda for comments on the manuscript. SK thanks Mousumi Dikpati, N. Andal and P. Ramadurai for computational help, and Rangan Lahiri for stimulating discussions.

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