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Magnetic field evolution of accreting neutron stars – III

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ABSTRACT

The evolutionary scenario of a neutron star magnetic field is examined assuming a spin-down induced expulsion of magnetic flux originally confined to the core, in a case in which the expelled flux undergoes ohmic decay. The nature of field evolution, for accreting neutron stars, is investigated incorporating the crustal microphysics and material movement resulting from accretion. This scenario may explain the observed field strengths of neutron stars but only if the crustal lattice contains a large amount of impurity, which is in direct contrast to the models that assume an original crustal field.

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

1 INTRODUCTION

There is as yet no satisfactory theory for the generation of the magnetic field of a neutron star. There are two main possibilities – the field can either be a fossil remnant from the progenitor star, or be generated after the formation of the neutron star (for a review see Bhattacharya & Srinivasan 1995, Srinivasan 1995 and references therein). Whereas post-formation generation mechanisms give rise to fields supported entirely by crustal currents (Blandford, Applegate & Hernquist 1983), the fossil field resides in the core of a neutron star. In the core, the rotation of the star is supported by the creation of Onsager–Feynman vortices in the neutron superfluid and the magnetic flux is sustained by Abrikosov fluxoids in the proton superconductor (Baym, Pethick & Pines 1969; Ruderman 1972; Bhattacharya & Srinivasan 1995).

Evidently no consensus regarding the theory of field evolution has been reached, because this depends crucially upon the nature of the underlying current configuration. Observations, though, indicate that the magnetic field decays significantly only if the neutron star is in an interacting binary (Bailes 1989; Bhattacharya 1991; Taam & van den Heuvel 1986). There have been three major theoretical endeavours to link the field evolution with the binary history of the star:

(i) expulsion of the magnetic flux from the superconducting core during the phase of propeller spin-down,
(ii) screening of the magnetic field by accreted matter and
(iii) rapid ohmic decay of the crustal magnetic field as a result of heating during accretion (see Bhattacharya 1995, 1999; Bhattacharya & Srinivasan 1995; Ruderman 1995 for detailed reviews).

Apart from screening, the other two models of field evolution depend on ohmic decay of the underlying current loops for a permanent decrease in the field strength. Such ohmic dissipation is possible only if the current loops are situated in the crust, where the electrical conductivity is finite. Models that assume an initial core–field configuration, therefore, require a phase of flux expulsion from the core. Muslimov & Tsygan (1985) and Sauls (1989) showed that there is likely to be a strong interpinning between the proton fluxoids and the neutron vortices. In a spinning down neutron star, the neutron vortices migrate outward and by virtue of the interpinning drag the proton fluxoids along to the outer crust. Srinivasan et al. (1990) pointed out that neutron stars interacting with the companion's wind would experience a major spin-down, causing the superconducting core to expel a large fraction of the magnetic flux. The nature of such flux expulsion as a result of spin evolution has been investigated in detail for both isolated pulsars (undergoing pure dipole spin-down) and for the neutron stars that are members of binaries (Ding, Cheng & Chau 1993; Jahan Miri & Bhattacharya 1994; Jahan Miri 1996). Recently, Ruderman, Zhu & Chen (1998) have investigated the outward (inward) motion of core superfluid neutron vortices during spin-down (spin-up) of a neutron star, which might alter the core's magnetic field in detail.

Jahan Miri & Bhattacharya (1994) and Jahan Miri (1996) have investigated the link between the magnetic field evolution and the rotational history of a neutron star resulting from the interaction of its magnetosphere with the stellar wind of its companion. They assumed an uniform ohmic decay time-scale in the crust, irrespective of the accretion rate. Later, Bhattacharya & Datta (1996) incorporated the crustal microphysics into their calculation of the ohmic diffusion of an expelled field. However this work did not include the material movement that takes place in the crust as a result of accretion. Assuming that the field evolution starts only after the process of flux expulsion is over, in the present work we

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incorporate the material movement and investigate the evolution of an expelled field in the crust of an accreting neutron star.

2 RESULTS AND DISCUSSION

Using the methodology developed by Konar & Bhattacharya (1997, hereafter Paper I), we solve the induction equation for an initial flux expelled at the core–crust boundary as a result of spin-down. 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, assuming the field to be purely poloidal. For our calculation we have assumed an initial g-profile following the profile used by Bhattacharya & Datta (1996) plotted in Fig. 1. The sharply peaked nature of the g-profile is caused by the flux expelled from the entire core being deposited in a thin layer, thereby substantially increasing the local field strength. The evolution of the crustal currents depends on the following parameters:

(i) the depth at which the currents are concentrated,
(ii) the width of the current distribution,
(iii) the impurity content of the crust and
(iv) the rate of accretion.

In the present work we assume the flux to be deposited at the bottom of the crust and therefore the depth of the initial current configurations is taken to be the thickness of the crust. The evolution of such flux is not very sensitive to the width of the current distribution (Bhattacharya & Datta 1996). Therefore we keep the width of the current distribution fixed for all of our calculations. For details of the computation, crustal physics and binary parameters, see Konar & Bhattacharya (1999, hereafter Paper II). As in earlier papers, we denote the impurity strength by the parameter

$$Q \equiv \sum_i \frac{n_i}{n}(Z_i - Z)^2 \qquad (1)$$

where n and Z are the number density and charge of background ions in the pure lattice and n_i and Z_i those of the ith impurity species. The sum extends over all species of impurities.

2.1 Field evolution with uniform accretion

In Fig. 2, we plot the evolution of the surface field for different values of the accretion rate. The field strengths go down by about only an order and a half in magnitude even for fairly large values of the impurity strength. The characteristic features of field evolution, with uniform accretion, are as follows.

(i) An initial rapid decay (ignoring the early increase) is followed by a slow-down and an eventual *freezing*.

(ii) The onset of 'freezing' is faster with higher rates of accretion.

(iii) Lower final 'frozen' fields are achieved for lower rates of accretion.

(iv) To achieve a significant reduction in the field strength, very large values of the impurity strength are required.

Hence, the general nature of field evolution in the case of an expelled flux is qualitatively similar to that in the case of an initial crustal flux (Paper I). However, to begin with the expelled flux is deposited at the bottom of the crust. Therefore the initial rapid decay that is observed in the case of a crustal field is not as dramatic as in the case of an initial crustal flux. Moreover, for higher rates of accretion the 'freezing' happens much earlier. For example, with an accretion rate of $10^{-9}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ the original crust is entirely assimilated into the core in about 10^7 yr. However, the surface field levels off long before that, because in this case the currents start returning to high-density regions even before they have had time to spread out in the outermost regions of the crust. For the same reason, large values of Q do not change the final surface field much for higher rates of accretion, as for high enough temperatures and high densities the conductivity ceases to be sensitive to the impurity content of the crust (see Paper I for details).

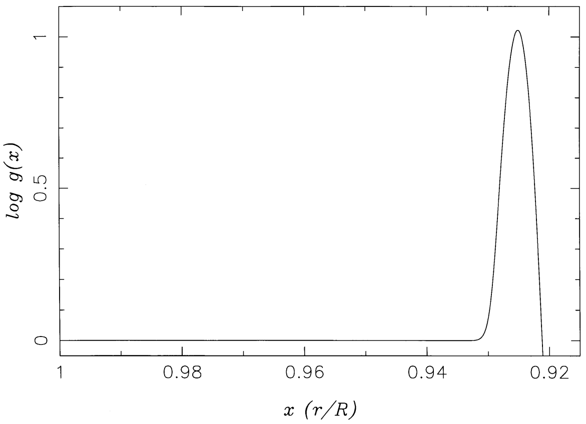

Figure 1. The initial radial g-profile in the crust immediately after expulsion.

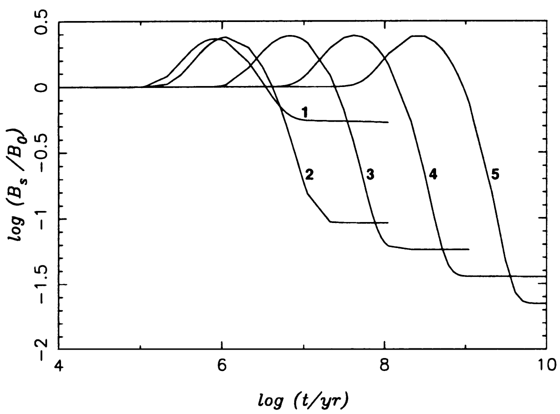

Figure 2. Evolution of the surface magnetic field for an expelled flux. The curves 1 to 5 correspond to $\dot{M} = 10^{-9}, 10^{-10}, 10^{-11}, 10^{-12}$ and $10^{-13}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. All curves correspond to $Q = 0.0$.

2.2 Field evolution in binaries

In Paper II, we considered three phases of binary evolution, namely the isolated, wind and Roche-contact phases. In the wind phase, there are two distinct possibilities of interaction between the neutron star and its companion. If the system is in the 'propeller phase' then there is no mass accretion. However, this phase is important because the star rapidly slows down to very long periods, and as a result significant flux expulsion is achieved. From the point of view of flux expulsion, therefore, we assume the flux to be completely contained within the superconducting core (neglecting the small flux expulsion caused by the dipole spin-down in the isolated phase) prior to this phase. The ohmic decay is assumed to take place only after this phase is over – that is in the phase of wind-accretion and in the phase of Roche contact. In the case of low-mass X-ray binaries, it is not very clear as to how long the phase of wind accretion lasts, or whether such a phase is realized at all after the 'propeller phase' is over. Therefore, in our calculations we have considered cases with and without a phase of wind accretion.

2.2.1 *High-mass binaries*

Fig. 3 shows the evolution of the surface field in high-mass X-ray binaries for different rates of accretion in the wind phase. The surface field shows an initial increase. This is followed by a sharp decay (of about an order of magnitude) only for sufficiently large rates of accretion in the wind phase. The decay in the Roche-contact phase is very small. In fact, the decay as seen in Fig. (3) is interrupted by Roche contact, in which the currents are quickly pushed to the core, thereby 'freezing' the field. This process also results in lower final field values for higher rates of accretion in the wind phase. Fig. (2) shows that the field indeed decays faster for higher rates of accretion to begin with, but the 'freezing' happens earlier for higher rates, thereby making the final saturation field lower for lower rates of accretion. Owing to the short-lived nature of the wind phase in massive binaries, the 'freezing' takes place before this saturation field is attained, giving rise to a behaviour (lower final field strengths for higher rates of accretion) contrary to that seen in low-mass binaries. For accretion rates appropriate to high-mass X-ray binaries the field decreases at most by an order of magnitude. This result is quite insensitive to the impurity strength of the crust, because the time available for the evolution before the currents are pushed back into the core is rather small.

2.2.2 *Low-mass binaries*

Fig. 4 shows the evolution of the surface field in low-mass X-ray binaries, for different values of the impurity concentration in the crust. It should be noted that a difference in the wind accretion rate does not manifest itself in either the nature of the field evolution or the final field strength. However, a difference in the accretion rate in the Roche-contact phase shows up very clearly. Comparing the different curves (for different values of the impurity parameter), we see that a large value of impurity strength gives rise to a rapid initial decay and therefore a lower value of the final surface field.

In Fig. 5, we have plotted the evolution of the surface field assuming the wind accretion phase to be absent. Once again we find that for higher rates of accretion, higher final field values are obtained. It should be noted here that the final field values obtained now are only about an order and a half of magnitude lower than the original surface field strengths, even though the impurity strengths assumed now are much higher than those assumed for the field evolution in low-mass X-ray binaries *with* a phase of wind accretion. In the absence of a prior phase of wind accretion, the flux does not have enough time to diffuse out to low-density regions when the Roche contact is established. Therefore the role of accretion, in the Roche-contact phase, is mainly to push the currents towards the high-density interior rather than to enhance the ohmic decay rate. Evidently, a much

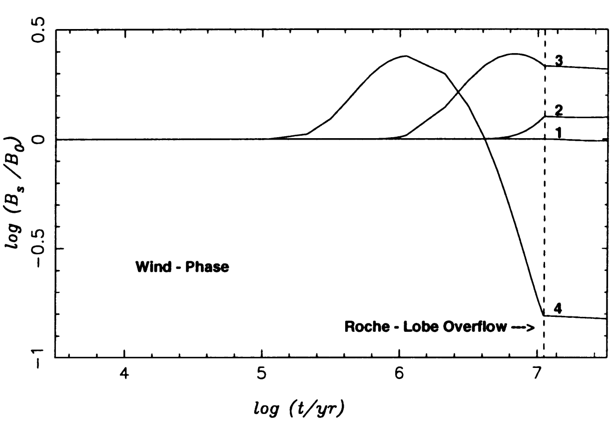

Figure 3. Evolution of the surface magnetic field in high-mass X-ray binaries for four values of the wind accretion rate. The curves 1 to 4 correspond to $\dot{M} = 10^{-13}, 10^{-12}, 10^{-11}$ and $10^{-10} \mathrm{M}_\odot \mathrm{yr}^{-1}$. All curves correspond to $Q = 0.0$.

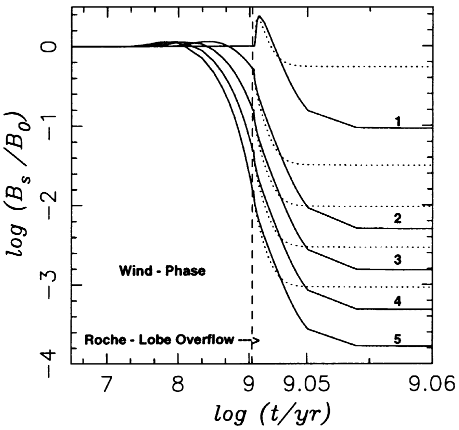

Figure 4. Evolution of the surface magnetic field in low-mass X-ray binaries. The dotted and the solid curves correspond to accretion rates of $\dot{M} = 10^{-9}$ and $10^{-10} \mathrm{M}_\odot \mathrm{yr}^{-1}$ in the Roche contact phase. The curves 1 to 5 correspond to $Q = 0.0$, 0.01, 0.02, 0.03 and 0.04, respectively. All curves correspond to a wind accretion rate of $\dot{M} = 10^{-16} \mathrm{M}_\odot \mathrm{yr}^{-1}$.

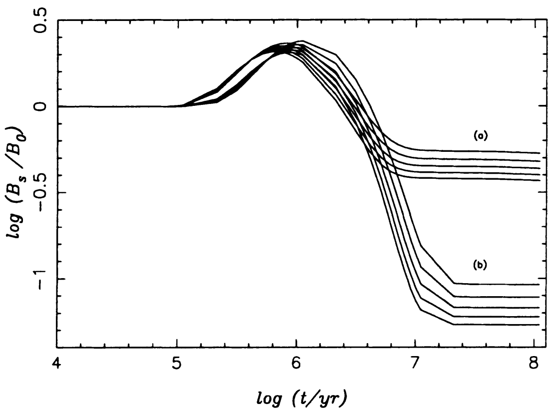

Figure 5. Evolution of the surface magnetic field in low-mass X-ray binaries without a phase of wind accretion. The set of curves (a) and (b) correspond to accretion rates of $\dot{M} = 10^{-9}$ and $10^{-10} \mathrm{M}_\odot \mathrm{yr}^{-1}$ in the Roche contact phase. Individual curves in each set correspond to $Q = 0.0$, 0.1, 0.2, 0.3 and 0.4 respectively, the upper curves being for the lower values of Q.

greater impurity strength is required for the final field values to decrease by three to four orders of magnitude. Unfortunately, our code is unable to handle high Q at present, because of the prohibitive requirement of computer time to ensure stability. However, this figure clearly establishes a trend as to how the final field values behave with Q, and it is evident that we need Q values much larger than those considered here to achieve millisecond pulsar field strengths in systems *without* a phase of wind accretion. Alternatively, systems without wind accretion might lead to high-field pulsars in low-mass binaries, such as PSR $0820+02$.

The most important point to note here is that similar to an initial crustal field configuration, the amount of field decay is much larger than that achieved in the case of high-mass X-ray binaries. Although in low-mass X-ray binaries the surface field does go down by three to four orders of magnitude from its original value for large values of impurity strength, the final field could remain fairly high if the impurity strength were small. If the wind-accretion phase is absent in these systems, then to achieve a large amount of field reduction even higher values of the impurity strength become necessary. Therefore, the ‘spin-down induced flux expulsion model’ will be consistent with the overall scenario of field evolution and, in particular, millisecond pulsars can be produced in low-mass X-ray binaries provided the impurity strength in the crust of the neutron stars is assumed to be extremely large.

The results of our investigation (the present work and that described in Paper II) clearly indicate that both the models, assuming an initial crustal field or, alternatively, a spin-down induced flux expulsion, place very stringent limits on the impurity strength. Whereas for the crustal model only $Q \lesssim 0.01$ is allowed, the results described here show that much larger values for impurity are needed in the latter model. These requirements are quite different. If there were an independent way of estimating the impurity content of the crust, then we could differentiate between these two models. However, in all of our investigations we have assumed that the impurity content of the crust does not change as a result of accretion, which may not be quite correct because accretion changes the crustal composition substantially (Hænsel & Zdunik 1990).

3 CONCLUSIONS

In this work we have investigated the consequences of ‘spin-down induced flux expulsion’. The general nature of field evolution seems to fit the overall scenario. The nature of the field evolution is quite similar to that in the case of a purely crustal model of field evolution, although the details differ. Most significantly, this model has the requirement of large values of the impurity strength Q, in direct contrast to the crustal model. Our findings are summarized below.

(i) The field values in the high-mass X-ray binaries can remain fairly large for a moderate range of impurity strength.

(ii) A reduction of three to four orders of magnitude in the field strength can be achieved in the low-mass X-ray binaries provided the impurity strength is as large as 0.05.

(iii) If the wind accretion phase is absent, then to achieve millisecond pulsar field values, an impurity strength in excess of unity is required.

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