Chapter 7

spin-down induced flux expulsion and its consequences

7.1 introduction

Almost all models of field evolution depend on the mechanism of ohmic decay of the underlying current loops for a permanent decrease in the field strength. It has been mentioned earlier (chapters [3] and [5]) that such ohmic dissipation is possible only if the current loops are situated in the crust where the electrical conductivity is finite. Any flux that may reside in the superconducting core of the star would remain unchanged forever unless this flux is brought out to the crust.

Models that assume an initial core-field configuration, therefore, require a phase of flux expulsion from the core. This expelled flux then undergoes ohmic dissipation in the crust decreasing the surface field strength. One such model uses the spin-evolution to achieve this - that of the 'spin-down induced flux expulsion'(Srinivasan 1989, Srinivasan et al. 1990). The core of the neutron star is believed to contain two superfluids - the neutral neutron superfluid and the charged proton superconductor. Whereas the rotation of the star is supported by creation of vortices in the neutron superfluid, the magnetic flux is sustained by Abrikosov fluxoids in the proton superconductor (Bhattacharya & Srinivasan 1995). Spinning down of the star requires a decrease in the number of vortices in the superfluid core. Therefore as a result of spin-down the vortices move out towards the core-crust boundary of the star. An inter-pinning between the vortices and the magnetic fluxoids make the fluxoids move outwards too, reducing their number in the core. A decrease in the number of fluxoids in the core reduces the field strength there. 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 (undergoing major spin-down in the 'propeller phase') (Ding, Cheng & Chau 1993; Jahan Miri & Bhattacharya 1994; Jahan Miri 1996).

In this chapter we look at the ohmic decay of such expelled field in the crust of an isolated as well as that of an accreting neutron star. Some of the earlier investigations in this direction assumed an uniform ohmic decay time-scale in the crust irrespective of the accretion rate (Jahan Miri & Bhattacharya 1994, Jahan Miri 1996). The only detailed work in this context has been by Bhattacharya & Datta (1996) where they incorporated the crustal micro-physics into their calculation for the evolution of the expelled field. However this work did not include the material movement that takes place in the crust as a result of accretion. In the present work we incorporate the material movement too and look at the evolution of an expelled field in the crust of an accreting neutron star using the methodology developed in chapter [5].

In the previous chapter we have discussed the overall scenario for the evolution of the neutron star magnetic field - encompassing both isolated neutron stars and those that are members of binary systems. In this chapter we investigate the consequences of the model of 'spin-down induced flux expulsion' in the above mentioned systems. We try to judge whether this model, too, is consistent with the overall field scenario and under what conditions. In section [7.2] we shall discuss the results of our computations and conclude in section [7.3].

7.2 results and discussions

Using the methodology developed in chapter [5] we solve the equation [5.16] for an initial flux just expelled at the core-crust boundary due to spin-down. Such an expelled flux is deposited at the bottom of the crust and we start our calculation with such a field configuration. Figure [7.1] shows the distribution of the g-function and figure [7.2] the toroidal currents, J_ϕ, assumed at the starting point of our evolution.

7.2.1 ohmic decay in isolated pulsars

The cause of flux expulsion is the spinning down of the pulsar. Therefore, for isolated pulsars too, experiencing a pure dipole slow-down, there would be some flux expulsion. The extent of such flux expulsion has been worked out by Jahan Miri (1996) and it has been shown tlicre that the flux expulsion is most effective for pulsars with large

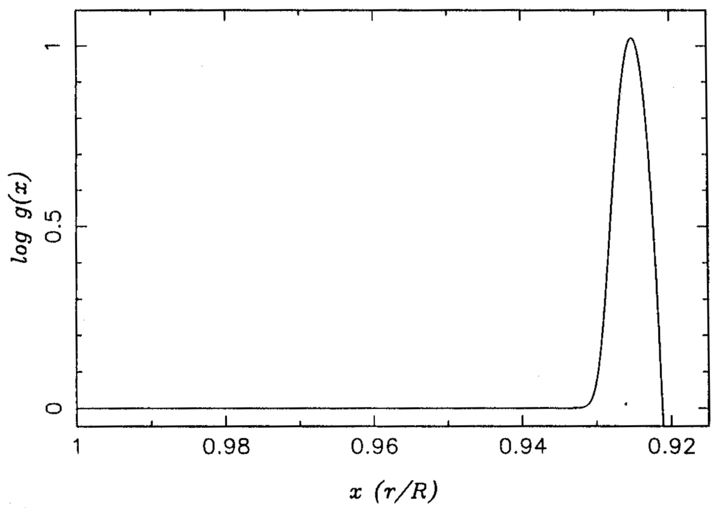


Figure 7.1: The initial radial dependence of the g-profile, corresponding to an expelled flux, centred at x = 0.925, with a width δx = 0.006; where x is the fractional radius r/R.

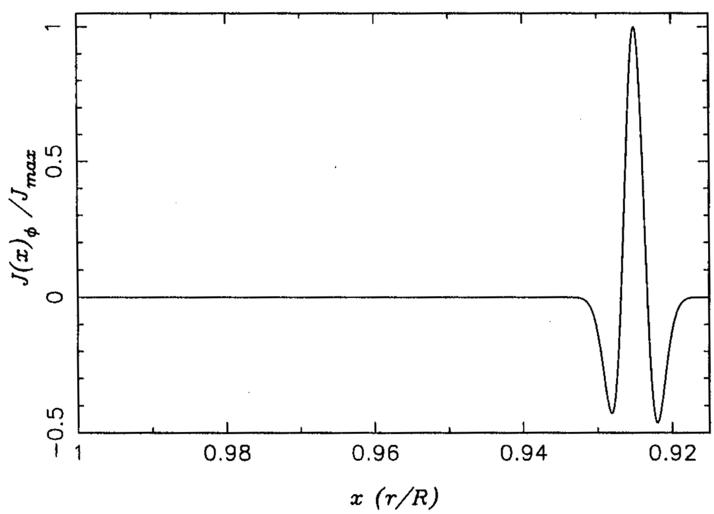


Figure 7.2: The initial radial dependence of the &component of the corresponding current configuration.

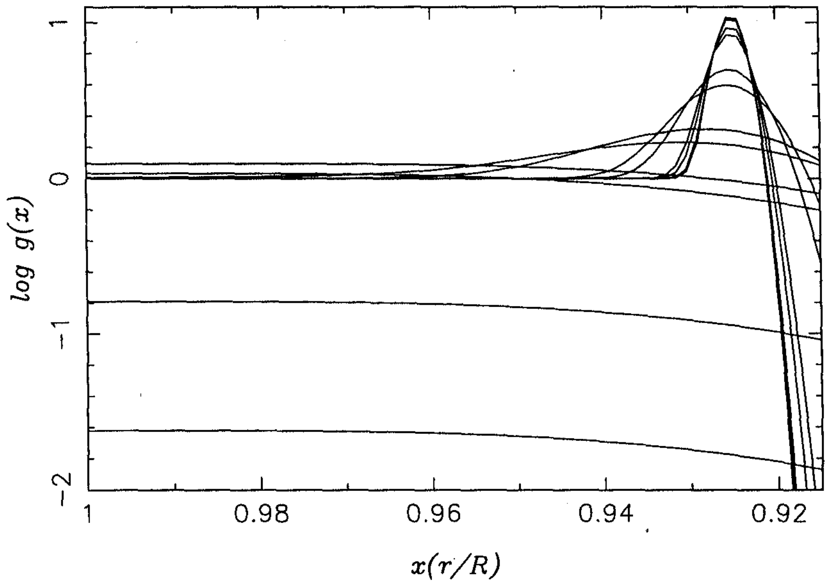


Figure 7.3: Pure ohmic diffusion of the g-profile plotted in figure [7.1] for $\tau \sim 10^9$ yrs, with Q = 0.1, in a neutron star with standard cooling. The curves are shown for intermediate times with no discernible change in the value at the surface (x = 1).

values of magnetic field strength. Before discussing the field evolution in neutron stars in binary systems, we first look at the ohmic decay of such an expelled field in isolated pulsars. We consider the isolated neutron star to undergo standard cooling, in order to find the maximum extent of field reduction in this case. But by the time significant flux-expulsion is achieved, the crustal temperature goes down to very low values for an isolated neutron star. In such a situation the conductivity would be mainly determined by the scattering of the conduction electrons by the impurities. To see the effect of that we have considered here several values of impurity strength Q (see section [2.4] for details).

In figures [7.3] and [7.4] we have plotted the time evolution of the g-profile for two values of the impurity strength. In figure [7.5] the corresponding evolution of the surface fields for five values of the impurity strength are plotted. It is seen very clearly that the surface field actually increases when the expelled flux diffuses outwards before finally decaying down to smaller values. It is to be noted that even for a very large value of the impurity strength (Q = 0.4) the surface field shows significant decay only over a time-scale of $\sim 10^9$ years. The active lifetime of an isolated radio pulsar is $\lesssim 10^8$ years. Therefore, an isolated radio pulsar would experience little field decay over its active lifetime, consistent with the indications from statistical analyses. So we conclude that

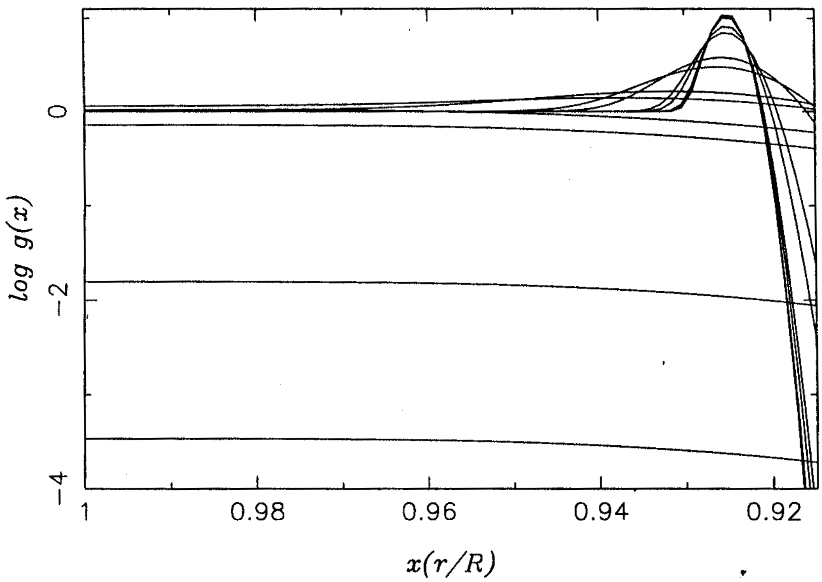


Figure **7.4:** Same as figure [7.3] with Q = **0.2.** The profiles show an initial increase and a substantial decrease in the surface value over a time-scale of 10^9 years.

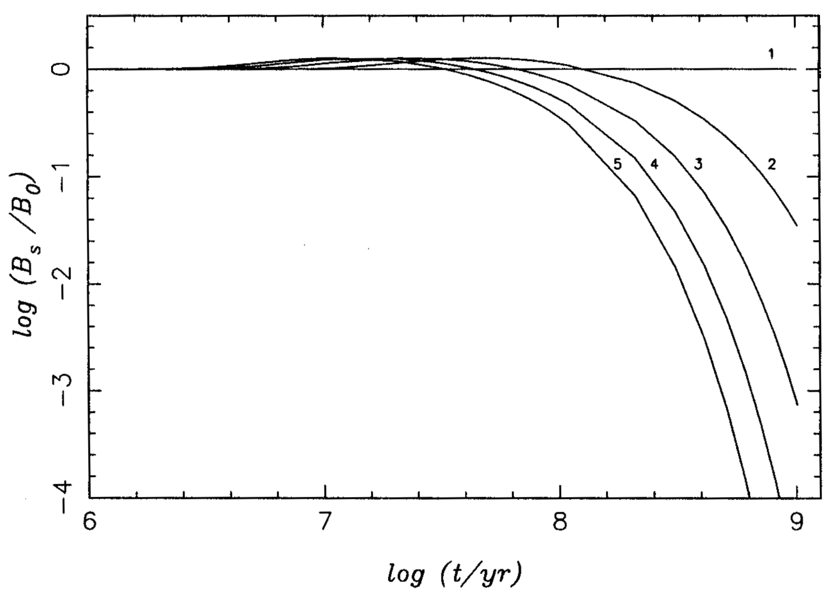


Figure 7.5: The evolution of the surface magnetic field due to pure diffusion of an expelled flux corresponding to the evolution of the g-profile plotted in the previous figures. The dotted and the solid curves correspond to Q = **0.0, 0.1, 0.2, 0.3** and **0.4** respectively.

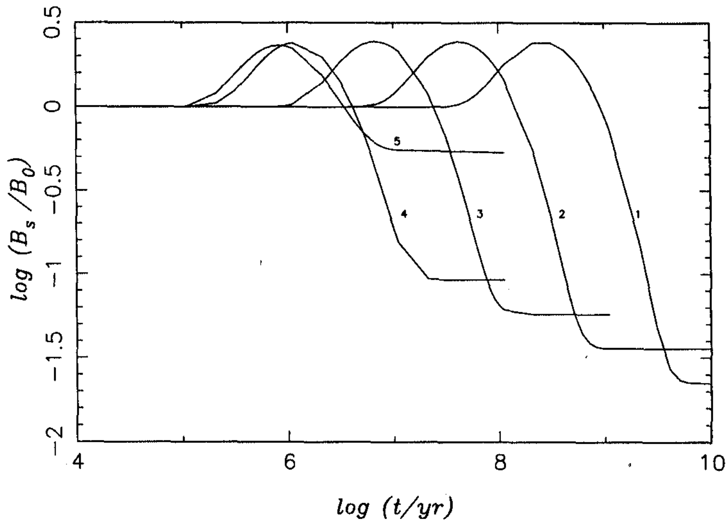


Figure 7.6: Evolution of the surface magnetic field for an expelled flux. The curves 1 to 5 correspond to $\dot{M} = 10^{-13}, 10^{-12}, 10^{-11}, 10^{-10}, 10^{-9}$ $M_\odot$ yr^{-1}. All curves correspond to Q = 0.0.

with an expelled flux there is provision for large values of Q to exist in the crust of the neutron star. In fact, we shall see later that in this model large Q is a necessary requirement for millisecond pulsar generation.

7.2.2 field evolution with accretion

Before looking into the nature of field evolution in various binary systems, we first investigate the evolution of the surface field under accretion, assuming the g-profile plotted in figure [7.1] as the initial condition. In figure [7.6] we plot the evolution of the surface field for different values of the accretion rate and in figure [7.7] we plot the evolution for different values of the impurity strength. We find that the field strengths go down by about only one and a half order of magnitude even for a fairly large value of the impurity strength. Therefore, even higher values of impurity strength will be required for a larger reduction in the field strength. We shall see later that for certain cases the required impurity strength is much larger than that considered by us here (we have considered a maximum Q value of 0.4) to achieve millisecond pulsar field values. The characteristic features of field evolution are then as follows.

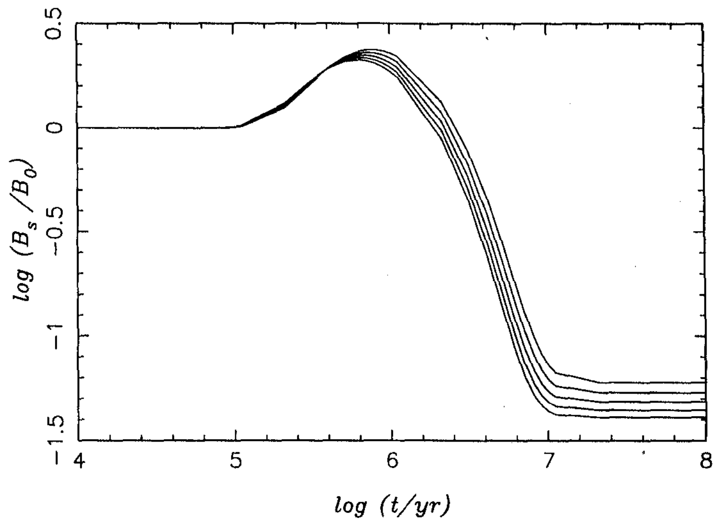


Figure 7.7: Evolution of the surface magnetic field for an expelled flux. The different curves from top to bottom correspond to Q = 0, 0.1, 0.2, 0.3 and 0.4 respectively. All curves correspond to to $\dot{M} = 10^{-10}$ $M_\odot$ yr^{-1}.

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

2. The onset of 'freezing' is faster with higher rates of accretion, i.e., at higher values of crustal temperature.

3. Lower final 'frozen' fields are achieved for lower rates of accretion.

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

It is clear from these features that 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. This indicates that the behaviour of the field evolution in different kinds of binaries will again be similar to what we have found in the case of an initial crustal flux, discussed in chapter [6].

7.2.3 field evolution in binaries

In section [6.3] we have outlined the three phase of binary evolution, namely - the isolated, the wind and the Roche-contact phase. In the wind phase there are two distinct

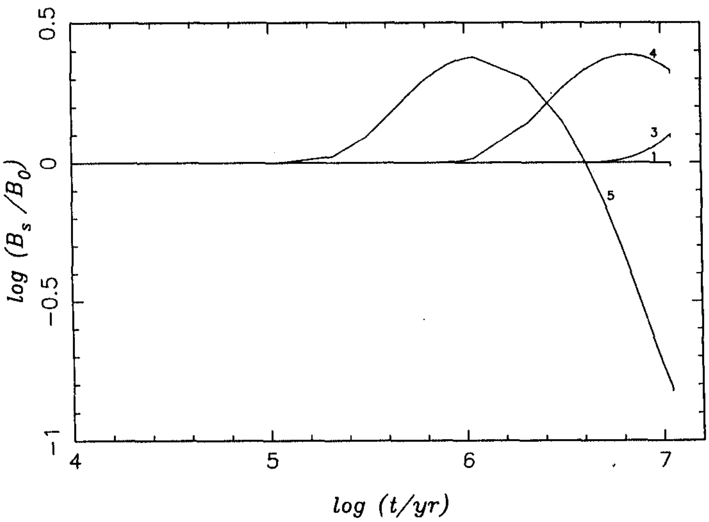


Figure 7.8: Evolution of the surface magnetic field in high mass X-ray binaries for four values of wind accretion rate. The curves 1 to 5 correspond to $\dot{M} = 10^{-14}, 10^{-13}, 10^{-12}, 10^{-11}, 10^{-10}$ $M_\odot$ yr^{-1}. Though here curves 1 and 2 are indistinguishable. All curves correspond to Q = 0.0.

possibilities of interaction between the neutron star and its main sequence companion. If the system is in the 'propeller phase' then there is no mass accretion. But the importance of this phase is that the star rapidly slows down to very long periods and as a result a 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. Therefore, the ohmic decay of this flux will take place only after this phase is over - that is in the phase of wind-accretion and most-importantly in the phase of Roche-contact. It has already been noted that, in 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 at all realized after the 'propeller phase' is over. Therefore, in our calculations we have considered cases with and without a phase of wind accretion, as before.

7.2.3.1 high mass binaries

Figures [7.8] and [7.9] show the evolution of the surface field in high mass X-ray binaries for different values of the impurity strength in the crust. The parameters for the

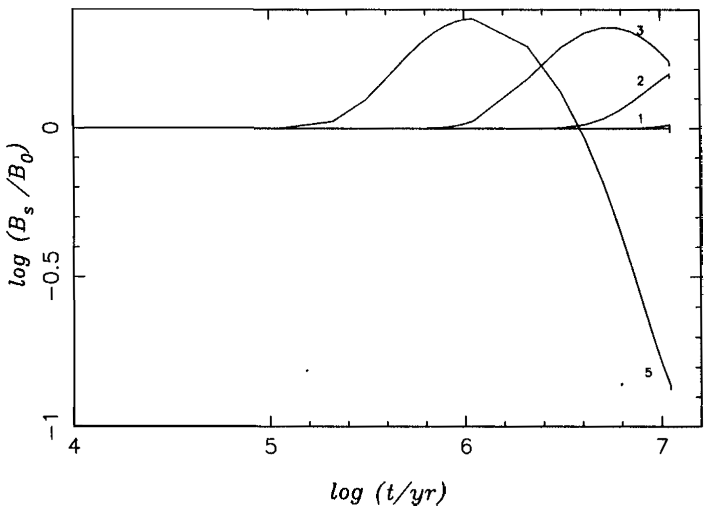


Figure 7.9: Same as figure [7.8] with Q = 0.04.

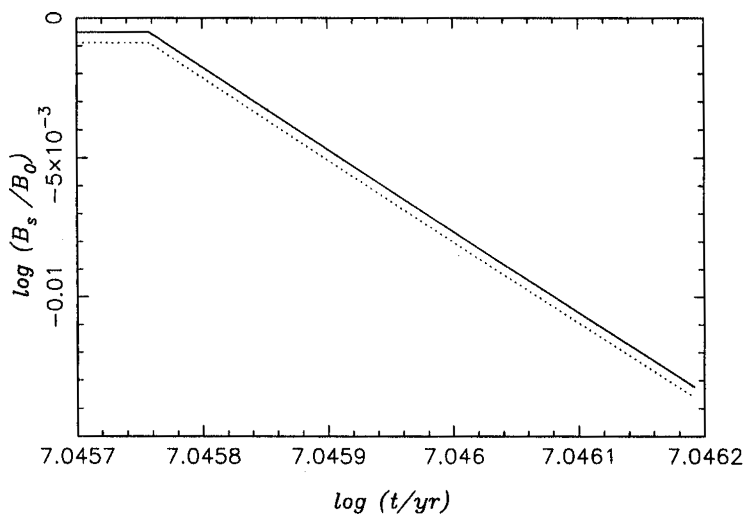


Figure 7.10: Same as figure [7.8] with the Roche-contact phase expanded.The solid and the dotted curves correspond to curves 1 and 2 in figure [7.8].

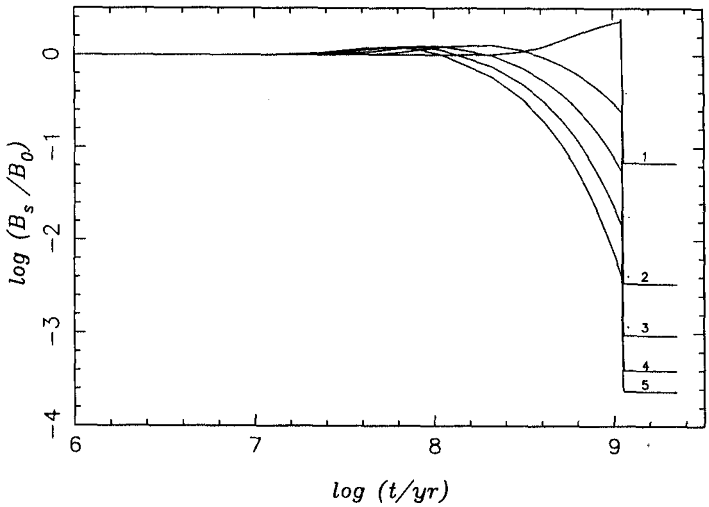


Figure 7.11: Evolution of the surface magnetic field in low mass X-ray binaries for two values of wind accretion rate. The curves 1 to 5 correspond to Q = 0.0, 0.01, 0.02, 0.03 and 0.04 respectively. All curves correspond to a wind accretion rate of $M = 10^{-16}$ $M_{\odot}$ yr^{-1}.

high mass X-ray binary evolution are as before. The surface field shows a clear initial increase followed by a sharp decay. The decay in the Roche-contact phase is very small and is almost invisible in the above-mentioned plots. In figure [7.10] we have expanded the Roche-phase corresponding to the figure [7.8] to highlight this phase. For the impurity strengths considered by us, the field decreases by about an order of magnitude.

7.2.3.2 low mass binaries

Figures [7.11] and [7.12] show the evolution of the surface field in the low mass X-ray binaries; for different values of the impurity concentration in the crust. The two figures correspond to two different values of accretion rate in the wind phase. It should be noted that this difference in the wind accretion rate does not manifest itself in either the nature of the field evolution or the final field strengths. However, a difference in the accretion rate in the Roche-contact phase shows up very clearly in figures [7.13] and [7.14] where the Roche-contact phases, corresponding to the figures [7.11] and [7.12], have been expanded. 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 decay and therefore a low value of the final surface field.

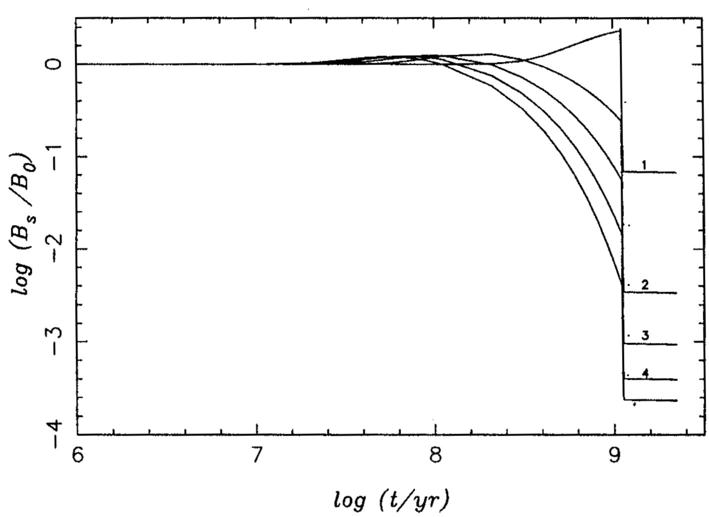


Figure 7.12: Same as figure [7.11] with a wind accretion rate of $\dot{M} = 10^{-14}$ $M_{\odot}$ yr^{-1}.

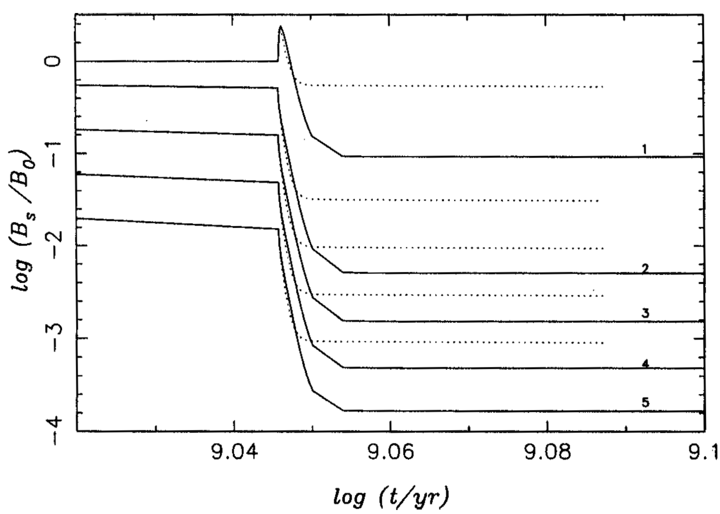


Figure 7.13: Same as figure [7.11] with the Roche-contact phase expanded. The solid and the dotted curves correspond to accretion rates of $\dot{M} = 10^{-10}, 10^{9}$ $M_{\odot}$ yr^{-1}in the Roche contact phase.

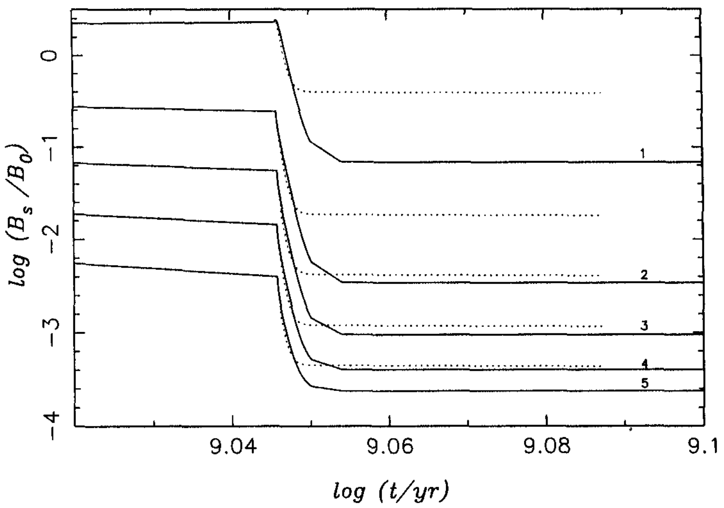


Figure 7.14: Same as figure [7.12] with the Roche-contact phase expanded.The solid and the dotted curves correspond to accretion rates of $\dot{M} = 10^{-10}, 10^{9}$ $M_\odot$ yr^{-1}in the Roche contact phase.

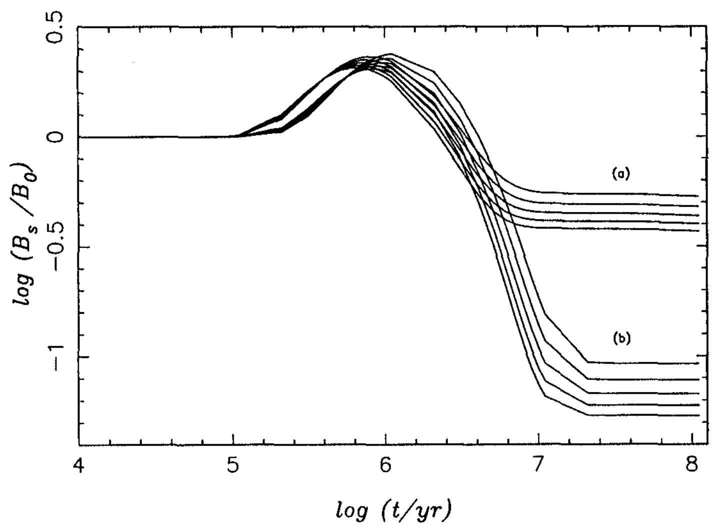


Figure 7.15: Evolution of the surface magnetic field in low mass X-ray binaries without a phase of wind accretion. The set of curves (a) and (b) correspond to accretion rates of $\dot{M} = 10^{-10}, 10^{9}$ $M_\odot$ yr^{-1}in the Roche contact phase. Individual curves in each set correspond to Q = 0.0, 0.1, 0.2, 0.3 and 0.4 respectively, the upper curves being for the lower values of Q.

In figure [7.15] 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 when we investigated the field evolution in low mass X-ray binaries *with* a phase of wind-accretion. In 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 here the role of accretion, in the Roche-contact phase, is mainly to push the currents in rather than to enhance ohmic decay rate. Evidently, much larger impurity strength is required to be assumed in order that the final field values could be reduced by three to four orders of magnitude. Unfortunately, due to numerical instabilities it becomes very difficult to explore situations with even higher values of Q. But the above-mentioned 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 get down to millisecond pulsar field strengths.

The most important point to note here is the fact that again, 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 with higher values of impurity strength the surface field does go down by three to four orders of magnitude from its original value, the final field strength could remain fairly large if the impurity strength is small. But if the wind-accretion phase is absent in these systems then to achieve large amount of reduction in the field strengths much larger value of the impurity strength will be required. 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.

7.3 conclusions

In this chapter we have investigated the consequences of 'spin-down induced flux expulsion'. So far, the general nature of field evolution seem to fit the overall scenario. The nature of field evolution is quite similar to that in case of a purely crustal model of field evolution though 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. To summarize then :

- The field in isolated neutron stars do not undergo any significant decay, over the active lifetime of the pulsar, conforming with the statistical analyses.
- The field values in the high mass X-ray binaries can reaming fairly large for a moderate range of impurity strength.
- 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 0.5.
- If the wind accretion phase is absent then to achieve ,millisecond pulsar field values, impurity strength in excess of unity is required.

Chapter 8

conclusions

In this final chapter we shall summarize the main conclusions of our investigations. For our work we have drawn upon many results which are not entirely free of uncertainties. We shall also mention here such uncertainties that are likely to affect our results. And lastly we shall indicate the future directions of work in this context.

1. **Generic Features of Field Evolution in the Crust –** In this thesis we have mainly investigated two models of field evolution that of an initial crustal current supporting the field and the model of spin-down induced flux expulsion. The qualitative features of field evolution are same for both the models. We have also looked at the effect of diamagnetic screening in an accreting neutron star. The nature of this screening is such that an assumption regarding a particular model of field configuration is unnecessary and the results of this investigation are model-independent. Therefore, we have the following general conclusions regarding the nature of field evolution in the crust.

   - Pure Ohmic Decay in Isolated Neutron Stars :

     (a) A slow cooling of the star gives rise to a fast decay and consequent low final field. The opposite happens in case of an accelerated cooling.

     (b) An initial crustal current distribution concentrated at lower densities again gives rise to faster decay and low final surface field. Whereas if the current is located at higher densities the decay is slow resulting in a higher final surface field.

     (c) A large value of impurity strength implies a rapid decay and low final field. If the crust behaves more like a pure crystal the decay slows down considerably.

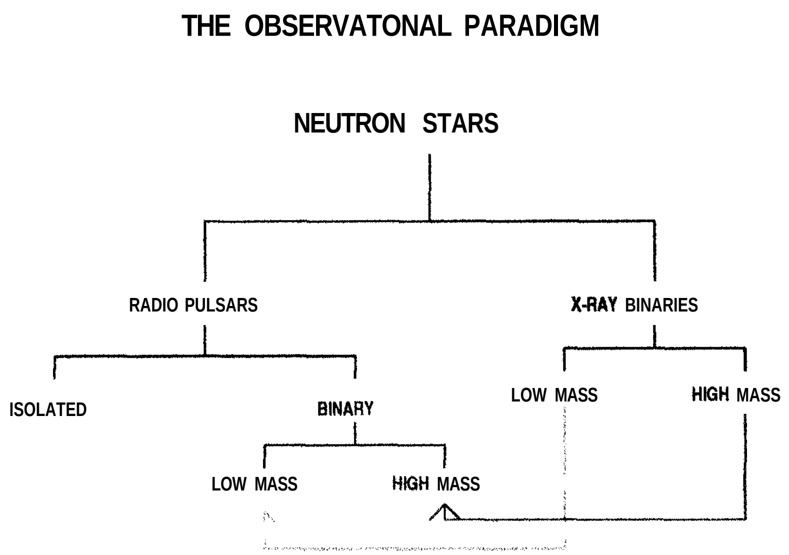
- Accretion-Induced Field Decay in Accreting Neutron Stars :

  (a) In an accreting neutron star the field undergoes an initial rapid decay, followed by slow down and an eventual *freezing*.

  (b) A positive correlation between the rate of accretion and the final field strength is observed, giving rise to higher final saturation field strengths for higher rates of accretion.

  (c) An expected screening of the surface field by the diamagnetic accreting material is rendered ineffective by the interchange instabilities in the liquid surface layers of the star.

2. **Nature of Field and Spin Evolution in Real Systems –** In the next phase of our investigation we have applied the models of field evolution to real systems - isolated neutron stars as well as to those in binaries. The paradigm of field evolution that have emerged out of various observations, statistical analyses and theoretical expectations have been summarized in the following flow-diagram. The arrows indicate the expected evolutionary link between X-ray binaries and binary radio pulsars. The following table summarizes the results of our investigations.



Evolution of a Purely Crustal Field Our Results		
system	final field and period	comment
isolated radio pulsars	high field, long period	no significant field decay in 10^9 years
HMXB	high field, long period	high-mass binary pulsars and solitary counterparts
	low field, long period	not active as pulsars
LMXB	high field, long period	high field low-mass binary pulsars and solitary counterparts
	low field, short period	low field low-mass binary pulsars and solitary counterparts, millisecond pulsars

It is evident that the results obtained from the field evolution models agree well with the observational paradigm. The nature of field evolution is similar for the model of spin-down induced flux expulsion. Though there is one major difference. To produce millisecond pulsars in LMXBs in spin-down induced flux expulsion model very large values of impurities are required. This makes *the surface field go down to very low values in* 10^9 *years in isolated pulsars* in contrast to a purely crustal model.

3. **Ranges of Physical Parameters –** In the following table we summarize the constraints on various physical parameters in the field evolution models placed by the requirement to match observed properties in a variety of systems. The parameters discussed here are - the density at which the initial crustal current distribution is located (ρ_0), the impurity strength in the crust (Q), the duration of wind-accretion phase in different binary systems and the rate of accretion in the Roche-contact phase for LMXBs.

Constraints on Physical parameters'				
parameter	model	system	requirement	parameter range
ρ_0	crustal	hmxb	high field	**high** ρ_0
Q	crustal	isolated radio pulsar	no field decay over active pulsar life-time	$Q \lesssim$ **0.01** for standard cooling, $Q \lesssim$ **0.05** for accelerated cooling
	core	LMXB	millisecond pulsar generation	$Q \gtrsim$ **0.05** with wind accretion, Q >> **1** without wind accretion
duration of wind accretion	crustal	HMXB	high field	short
M in Roche-phase	crustal	LMXB	high field	Eddington rate

4. **Uncertainties –** The results and conclusions stated above suffer from a number of uncertainties regarding the micro-physics of the neutron star, as listed below.

- Thermal Behaviour -

  (a) Isolated Phase - The present date can be made to fit scenarios with both a ***slow*** or an *accelerated* cooling. Hence it is not clear which is the correct cooling behaviour of an isolated neutron star.

  (b) Accreting Phase - the crustal temperature corresponding to a given rate of accretion has not been determined with any certainty. Also, the existing results are limited in their scope and there is no agreement between various authors.

  (c) Post-Accretion Phase - No calculation exists for the thermal behaviour of this phase at all.

- Transport Properties - There are several factors, the effects of which have not been incorporated yet, namely those of
    (a) the change in the chemical composition due to a) accretion and b) spin-down; and
    (b) the dislocations, defects etc. of the crustal lattice.
- Equation of State - Apart from the uncertainties already existent for a cold equation of state, the change in the chemical composition due to accretion introduces change in the equation of state and hence in a) the structure of the star and its b) transport properties.
- All of our investigation has been based on an assumption of a pure dipolar model for the magnetic field. The validity of these results requires to be checked by including higher order multi-poles for the field.

5. **Future Directions** – One of the most important questions in the context of the evolution of magnetic fields in neutron stars is regarding the models of field generation (and therefore of the internal field configuration). There is no consensus as to which one is actually realized. Our calculations clearly point out that the models have very different requirements for the impurity strength in the crust. Possible ways of resolving this dilemma then could be the following.

    - Theoretical - A better many-body calculations may determine the state of matter in the crust accurately in regard to its impurity content.
    - Observational Prediction - An old solitary radio pulsar will have a very low field if the impurity content of the crust is very large. The detection of such a pulsar accreting matter from the interstellar matter will therefore immediately indicate the impurity content of the crust. The results of our investigation clearly indicate that the both the models place very stringent limits on the impurity strength and the limits from the different models are quite incompatible. Therefore such an observation will immediately determine the viability of one model or the other - predictably providing an answer to this question.

Bibliography

[1] Alpar M. A., 1991, Neutron Stars : Theory and Observation, ed. Ventura J., Pines D., Kluwer academic Publishers

[2] Alpar M. A., Cheng A. F., Ruderman M. A., Shaham J., 1982, Nat, 300, 723

[3] Ainsworth T. L., Wambach J., Pines D., 1989, Phys.Lett., B222, 173

[4] Ashcroft N. W., Mermin N. D., 1976, Solid State Physics, Holt, Reinhart & Winston

[5] Baade W., Zwicky F., 1934, Proc.Natn.Acad.Sci., 20, 254

[6] Backer D. C., Kulkarni S. R., Heiles C. E., Davis M. M., Goss W. M., 1982, Nat, 300, 615

[7] Baiko D. A., Yakovlev D. G., 1995, Astron.Lett., 21, 702

[8] Bailes M., 1996, Pulsars : Problems and Progress, ed. Johnston S., Walker M. A., Bailes M., ASP Conference Series Vol.105

[9] Baym G., Bethe H. A., Pethick C., 1971, Nucl.Phys., A175, 225

[10] Baym G., Pethick C., Pines D., 1969, Nat, 224, 675

[11] Baym G., Pethick C., Sutherland P., 1971, ApJ, 170, 299

[12] Bhattacharya D., 1995a, JA&A, 16, 227

[13] Bhattacharya D., 1995b, X-Ray Binaries, ed. Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., Cambridge University Press

[14] Bhattacharya D., 1996a, Pulsars : Problems and Progress, ed. Johnston S., Walker M. A., Bailes M., ASP Conference Series Vol.105

[15] Bhattacharya D., 1996b, Pulsar Timing, General relativity and the Internal *Structure* of Neutron Stars, Royal Netherlands Academy of Arts and Sciences, in press.

[16] Bhattacharya D., Datta B., 1996, MNRAS, 282, 1059

[17] Bhattacharya D., Srinivasan G., 1986, Curr. Sci., 55, 327

[18] Bhattacharya D., Srinivasan G., 1991, JA&A, 12, 17

[19] Bhattacharya D., Srinivasan G., 1995, X-Ray Binaries, ed. Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., Cambridge University Press

[20] Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1

[21] Bhattacharya D., Wijers R. A. M. J., Hartman J. W., Verbunt F., 1992, A&A, 254, 198

[22] Bildsten L., Cutler C., 1995, ApJ, 449, 800

[23] Bisnovatyi-Kogan *G*. S., Komberg B. V., 1974, SvA, 18, 217

[24] Blandford R. D., Applegate J. H., Hernquist L. 1983, MNRAS, 204, 1025

[25] Blandford R. D., DeCampli W. M., Konigl A., 1979, BAAS, 11, 703

[26] Callanan P. J., Charles P. A., Hassal B. M. J., Machin G., Mason K. O., Naylor T., Smale A. P., 1989, MNRAS, 238, 25P

[27] Camilo O. F., Nice D. J., Shrauner J. A., Taylor J. H., ApJ, 469, 819

[28] Chabrier G., Potekhin A. Y., Yakovlev D. G., 1997, ApJ, 205, 541

[29] Chandrasekhar S., 1931, Phil.Mag., 11, 592

[30] Chen K., Ruderman M., 1993, ApJ, 408, 179

[31] Cheng K. S., Dai Z. G., 1997, ApJ, 476, L39

[32] Cordes J. M., Chernoff D. F., 1997, ApJ, 482, 971

[33] Cordes J. M., Wolzscan A., Dewey R. J., Blaskiewicz M., Stinebring D. R., 1990, ApJ, 349, 121

[34] Datta B., Thampan A. V., Bhattacharya D., 1995, JA&A, 16, 375

[35] Ding K. Y., Cheng K. S., Chau H. T., 1993, ApJ, 408, 167

[36] Feynman R. P., Metropolis N., Taylor E., 1949, Phys.Rev., 75, 1561

[37] Friedman B., Pandharipande V. R., 1981, Nucl.Phys., A361, 502

[38] Fruchter A. S., Steinbring D. R., Taylor J. H., 1988, Nat, 333, 237

[39] Fujimoto M. Y., Hanawa T., Iben I. Jr., Richardson M. B., 1984, ApJ, 278, 813

[40] Geppert U., Urpin V. A., 1994, MNRAS, 271, 490

[41] Geppert U., Urpin V. A., Konenkov D., 1996, A&A, 307, 807

[42] Geppert U., Wiebicke H. J., 1991, A&AS, 87, 217

[43] Geppert U., Wiebicke H. J., 1995, A&A, 300, 429

[44] Ginzburg V. L., 1964, Sov.Phys.Doklady, 9, 329

[45] Ginzburg V. L., Kirzhnits D. A., 1964, Zh.Eksperim.Theor.Fiz., 47, 2006

[46] Gold T., 1968, Nat, 218, 731

[47] Gold T., 1969, Nat, 221, 25

[48] Gudmundsson E. H., Pethick C. J., Epstein R. J., 1982, ApJ, 259, L19

[49] Gudmundsson E. H., Pethick C. J., Epstein R. J., 1983, ApJ, 272, 286

[50] Gunn J. E., Ostriker J. P., 1968, Nat, 221, 454

[51] Gunn J. E., Ostriker J. P., 1970, ApJ, 160

[52] Hanawa T., 1992, Structure and Evolution of Neutron Stars, ed. Pines D., Tamagaki R., Tsuruta S., Addison-Wesley

[53] Hameury J. M., Bonazzola S., Heyvaerts J., Lasota J. P., 1983, A&A, 128, 369

[54] Hansen B. M. S., Phinney E. S., 1997, MNRAS, (in press)

[55] Hartman J. W., Verbunt F., Bhattacharya D., Wijers R. A. M. J., 1997, A&A, 322, 477

[56] Haensel P., Zdunik J. L., Dobaczewski J., 1989, A&A, 222, 353

[57] Hasinger G., van der Klis M., 1989, A&A, 225, 79

[58] Hewish A., Bell S. J., Pilkington D. H., Scott P. F., Collins R. A., 1968, Nat, 217, 709

[59] Hulse R. A., Taylor J. H., 1975, ApJ, 195, L51

[60] Itoh N., 1994, The Equations of State *in* Astrophysics, IAU Colloquium No. 147, ed. Chabrier G., Cambridge University Press

[61] Itoh N., Hayashi H., Kohyama Y., 1993, ApJ, 418, 405

[62] Iwamoto N., Qin L., Fukugita M., Tsuruta S., 1995, Rhys.Rev., D51, 348

[63] Jahan Miri M., 1996, MNRAS, 283, 1214

[64] Jahan Miri M., Bhattacharya D., 1994, MNRAS, 269, 455

[65] Jackson J. D., 1975, Classical Electrodynamics, 2nd ed., John Wiley & Sons

[66] King A., Frank J., Kolb U., Ritter H., 1995, ApJ, 444, 37 van den Heuvel E. P. J., Cambridge University Press

[67] Koester D., Chanmugam G., 1990, Rep.Prog.Phys., 53, 837

[68] Konar S., Bhattacharya D., Urpin V., 1995, JA&A, 16, 249

[69] Konar S., Bhattacharya D., 1997, MNRAS, 284, 311

[70] Kulkarni S. R., 1986, ApJ, 306, L85

[71] Kulkarni S. R., Djorgovski S., Klemola A. R., 1990, ApJ, 367, 221

[72] Lattimer J. M., 1992, Structure and Evolution of Neutron Stars, ed. Pines D., Tamagaki R., Tsuruta S., Addison-Wesley

[73] Lattimer J. M., Pethick C. J., Prakash M., Haensel P., 1991, Phys.Rev.Lett., 66, 2701

[74] Lorenz C. P., Ravenhall D. G., Pethick C. J., 1993, Phys.Rev.Lett., 70, 379

[75] Lorimer D. R., 1994, The Galactic Population of Millisecond and Normal Pulsars, Ph. D. thesis, University of Manchester, U.K.

[76] Lorimer D. R., 1995, MNRAS, 274, 300

[77] Lyne A. G., Anderson B., Salter M. J., 1982, MNRAS, 201, 503

[78] Manchester R. N., Taylor J. H., 1977, Pulsars, W.H.Freeman and Company, San Francisco

[79] Miralda-Escudé J., Haensel P., Paczyński B., 1990, ApJ, 362, 572

[80] Negele J. W., Vautherin D., 1973, Nucl.Phys., A207, 298

[81] Nicastro L., Johnston S., 1995, MNRAS, 262, 929

[82] Nice D. J., Taylor J. H., 1995, ApJ, 441,429

[83] Oppenheimer J. R., Volkoff G. M., 1939, Phys.Rev., 55, 379

[84] Ostriker J. P., Gunn J. E., 1969, ApJ, 157, 1395

[85] Pacini F., 1967, Nat, 216, 567

[86] Pacini F., 1968, Nat, 219, 145

[87] Page D., 1997, (http://xxx.lanl.gov/astro-ph/9706259)

[88] Pandharipande V. R., Pines D., Smith R. A., 1976, ApJ, 208, 550

[89] Pavlov G. G., Zavlin V. E., Trümper J., Neuhauser R., 1996, ApJ, 472, L33

[90] Pethick C. J., 1992, Rev.Mod.Phys., 64, 1133

[91] Pethick C. J., Ravenhall D. G., 1992, Phil.Trans.R.Soc., A341, 17

[92] Pethick C. J., Thorsson V., 1994, Phys.Rev.Lett., 72, 1964

[93] Pines D., 1991, *Neutron Stars : Theory and Observations,* ed. Ventura J., Pines D., Kluwer academic Publishers, London

[94] Pines D., Alpar M. A., 1992, *Structure and Evolution of Neutron Stars,* ed. Pines D., Tamagaki R., Tsuruta S., Addison-Wesley

[95] Prakash M., 1994, Phys.Rep., 242, 297

[96] Prakash M., Prakash M., Lattimer J., Pethick C. J., 1992, ApJ, 208, 550

[97] Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, *Numerical Recipes in Fortran : The Art of Scientific Computing, Ch. 19,* Cambridge University Press

[98] Potekhin A. Y., 1997, A&A, (in press)

[99] Potekhin A. Y., Yakovlev D. G., 1997, A&A, (in press)

[100] Psaltis D., Lamb F. K., 1997, preprint

[101] Radhakrishnan V., Srinivasan G., 1982, Curr.Sci., 51, 1096

[102] Ramachandran, R., Bhattacharya, D., 1997, MNRAS, 288, 565

[103] Romani R. W., 1990, Nat, 347, 741

[104] Romani R. W., 1995, Isolated Pulsars, ed. van Riper K., Epstein R., Ho C., Cambridge University Press

[105] Ruderman M., 1991a, ApJ, 366, 261

[106] Ruderman M., 1991b, ApJ, 382, 576

[107] Ruderman M., 1991c, ApJ, 382, 587

[108] Ruderman M., 1995, JA&A, 16, 207

[109] Rudernian M., Shaham J., Tavani M., 1989, ApJ, 336, 507

[110] Ruderman M., Sutherland P. G., 1973, Nature Phys.Sci., 246, 93

[111] Sang Y., Chanmugam G., 1987, ApJ, 323, L61

[112] Savonije G., 1978, A&A., 309, 171

[113] Schaab Ch., Herman B., Weber F., Weigel M. K., 1997, ApJ, 480, L111

[114] Schaab Ch., Voskresenskii D., Sedrakian A. D., Weber F., Weigel M. K., 1997, A&A, 321, 591

[115] Shapiro S. L., Teukolsky S. A., 1983, Black Holes, White Dwarfs and Neutron Stars, John Wiley & Sons Inc.

[116] Shibanov Y. A., Yakovlev D. G., 1996, A&A, 309, 171

[117] Shibazaki N., Murakami T., Shaham J., Nomoto K., 1989, Nat, 342, 656

[118] Slattery W. L., Doolen G. D., DeWitt H. E., 1982, Phys.Rev., A26, 2255

[119] Spruit H. C., 1983, Solar and Stellar Magnetic Fields : Origins and Coronal Effects, IAU Symposium No. 102, ed Stenflo J. O., D. Reidel Publishing Company

[120] Srinivasan G., 1989, A&ARv, 1, 209

[121] Srinivasan G., 1995, Stellar Remnants, Saas-Fee Advanced Course 25, ed. Meynet G., Sherev D., Springer-Verlag

[122] Srinivasan G., van den Heuvel E. P. J., 1980, A&A, 108, 143

[123] Srinivasan G., Bhattacharya D., Muslimov A. G., Tsygan A. T., 1990, Curr.Sci., 59, 31

[124] Taam R. E., van den Heuvel E. P. J., 1986, ApJ, 305, 235

[125] Tatsumi T., Muto T., 1992, Structure and Evolution *of* Neutron Stars, ed. Pines D., Tamagaki R., Tsuruta S., Addison-Wesley

[126] Triimper J., Pietsch W., Reppin C., Voges W., Staubert R., Kendziorra E., 1978, ApJ, 219, L105

[127] Urpin V. A., Geppert U., 1995, MNRAS, 275, 1117

[128] Urpin V. A., Geppert U., 1996, MNRAS, 278, 471

[129] Urpin V. A., Levshakov S. A., Yakovlev D. G., 1986, MNRAS, 219, 703

[130] Urpin V. A., Muslimov A. G., 1992, MNRAS, 256, 261 .

[131] van den Heuvel E. P. J., 1992, X-ray Binaries and Recycled Pulsars, ed. van den Heuvel E. P. J., Rappaport S., Kluwer academic Publishers, Dordrecht

[132] van den Heuvel E. P. J., 1995, JA&A, 16, 227

[133] van den Heuvel E. P. J., van Paradijs J. A., Taam R. E., 1986, Nat, 322, 153

[134] van den Heuvel E. P. J., Bitzaraki O, 1995, A&A, 297, L41

[135] Van Riper K. A, 1991a, ApJS, 75, 449

[136] Van Riper K. A, 1991b, ApJ, 372, 251

[137] Verbunt F., van den Heuvel E. P. J., 1995, X-Ray Binaries, ed. Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., Cambridge University Press

[138] Verbunt F., Wijers R. A. M. J., Burm H., 1990, A&A, 234, 195

[139] Wakatsuki S., Hikita A., Sato N., Itoh N., 1992, ApJ, 392, 628

[140] Wendell C. E., van Horn H. M., Sargent D., 1987, ApJ, 313, 284

[141] Wiebicke H. J., Geppert U., 1991, A&A, 245, 331

[142] Wiebicke H. J., Geppert U., 1992, A&A, 262, 125

[143] Wiebicke H. J., Geppert U., 1995, A&A, 294, 303

[144] Wiebicke H. J., Geppert U., 1996, A&A, 309, 203

[145] Wijers R. A. M. J, 1996, MNRAS, 287, 607

[146] Wiringa R. B., Fiks V., Fabrocini A., 1988, Phys.Rev., C38, 1010

[147] White N. E., Zhang C. M., 1997, preprint

[148] Woltjer L., 1964, ApJ, 140, 1309

[149] Wolszcan A., 1994, Science, 264, 538

[150] Woosley S. E., Wallace R. K., 1982, ApJ, 258, 716

[151] Yakovlev D. G., Urpin V. A., 1980, SvA, 24,303

[152] Young E. J., Chanmugam G., 1995, ApJ, 442, L53

[153] Zdunik J. L., Haensel P., Paczynski B., Miralda-Escudé J., 1992, ApJ, 384,129

[154] Zhang C. M., 1997, preprint

[155] Zhang C. M., Wu X. J., Yang G. C., 1994, A&A, 283, 889