Evolution of the Magnetic Field in Accreting Neutron Stars

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By

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Declaration

I hereby declare that the work reported in this thesis is entirely original. It was carried out by me at Raman Research Institute under the auspices of Joint Astronomy Program of the Department of Physics, Indian Institute of Science, Bangalore. I further declare that it has not formed the basis for the award of any degree, diploma, membership, associateship or similar title of any university or institution.

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Contents

Chapter 1

introduction

Thirty years of active research in Pulsars have made it abundantly clear that these objects are veritable laboratories for testing out theories for exotic physics stretching far beyond the limits of present day terrestrial experiments. Indeed, the 1967 discovery of the first pulsar by Hewish and his group (Hewish et al., 1968) in Cambridge has been one of the major events in recent astronomy. Pulsars, characterized by the regular pulses of radiation observed to be coming from them, are actually strongly magnetized neutron stars rotating very rapidly. The concept of neutron stars, of course, has been around for about thirty years before this discovery, almost from the day the neutron was detected for the first time. It is said that the day the news of the discovery of neutrons reached Landau, he hypothesized on the possible existence of stars made up entirely of neutrons. Barely two years after this, Baade & Zwicky (1934) in their seminal paper propounded the theory of the possible birth of neutron stars in the most violent and spectacular event of stellar death, that of a supernova explosion.

There has always been a great interest in the ultimate fate of the stars. Before the advent of Fermi-Dirac statistics, it was inconceivable as to how a star could escape the final collapse at the hands of gravity when it exhausts its nuclear fuel - a view expounded by Sir Arthur Eddington. But the work of Chandrasekhar (1931) proved conclusively that the final gravitational collapse could be halted when the stellar material becomes Fermi-degenerate due to extreme compression so that the degeneracy pressure is sufficient to withhold gravity. In this work the case of electron-degeneracy and the end state of stars that we know of as white dwarfs has been discussed. Soon afterwards the companion of Sirius was identified as a white dwarf which vindicated the existence of such degenerate end stages of stars. The logical extension of Chandrasekhar's argument is, of course, the state when the neutrons become degenerate. And that is the state found in neutron stars.

Even before the discovery of pulsars, Pacini (1967) suggested that the Crab Nebula must be powered by a rotating neutron star. The Crab Nebula is the remnant of the supernova of A.D. 1054, recorded by the Chinese. The later identification of the Crab Pulsar with the neutron star associated with the supernova gave the first direct proof of Baade & Zwicky's hypothesis. Lately, the attention has been focussed on the most spectacular supernova of recent times, SN1987A, a supernova that went off in the Large Magellanic Cloud, a small companion galaxy of the Milky Way, in February 1987. But even after a decade of intense search the neutron star that is supposed to be there has remained elusive. This, in all probability, means a modification of the theory of neutron star formation in supernovae. Of course, supernovae may not be the only way of neutron star formation. Recently, particularly in connection with the possible ways of millisecond pulsar formation, the theory of accretion-induced collapse of a white dwarf into a neutron star has been advocated. Even if that does happen in certain systems, supernovae would still most likely be the major route through which the neutron stars are born. As a star of main-sequence mass $\gtrsim 8 M_{\odot}$ explodes at the end of its life, it throws away most of its mass and the object that is left behind is a neutron star of mass of about $\sim 1.4\ M_{\odot}$ with a radius of ten kilometers. Evidently the formation of this ultra-compact object is accompanied by a release of a tremendous amount of energy ($\sim 10^{53}$ erg) equal to the binding energy of it. And this is the energy that powers the fantastic fireworks of a supernova.

The initial interest in neutron stars, surprisingly, arose due to the discovery of certain intense radio emitters. The large values of red-shift associated with these objects made one think that these could be neutron stars producing highly red-shifted radiation due to the large value of their surface gravity. That idea died its natural death when quasars were discovered. Then in 1967 pulsars were discovered almost serendipitously, by Jocelyn Bell, a graduate student working with Anthony Hewish on interplanetary scintillation (Hewish et al., 1968). Understandably, the first signals from the neutron star, due to their extreme regular periodicity, were suspected to have been signatures of the 'little green men'. But all such highly speculative theories and their more sober counterparts quickly settled to an identification of these objects as neutron stars (Gold, 1968, 1969). The signals were understood to have originated due to the fast rotation of the neutron stars possessing very large magnetic fields (canonical value of the field being $B \sim 10^{12}$ Gauss). Extremely compact objects were required to explain the rapidity of the pulses (P m s) and the obvious candidates were the neutron stars and the white dwarfs. Discovery of fast pulsars like Crab and Vela (with rotation periods of 33 and 89 ms respectively) excluded the possibility of these being white dwarfs (as they would not be gravitationally stable at such high rates of rotation) and the identification of pulsars with neutron stars was conclusively established (Gold 1968, 1969; Gunn & Ostriker 1968; Pacini 1968).

Pulsars are characterized by their pulsed emission and the precise periodicity of these pulses, though the shape and the amplitude of the pulse profiles vary widely. The mechanism of the radio emission still remains one of the important unsolved problems of pulsar physics, though the basic ideas were laid down quite early on by Ostriker & Gunn (1969). In this model of ***magnetic dipole*** pulsar emission is derived from the kinetic energy of a rotating neutron star. It is assumed, that a neutron star rotates uniformly in vacuum at a frequent w and has a dipole moment m at an angle 8 to the axis of rotation. The dipole field at the magnetic pole of the star; B_p, is related to m by

$$|\mathbf{m}| = \frac{1}{2}B_pR^3, \tag{1.1}$$

where R is the radius of the star. This ***oblique rotator*** configuration has a time-varying dipole moment as seen from infinity and therefore radiates energy at a rate

$$\begin{aligned} \dot{E} &= -\frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 \\ &= -\frac{1}{6c^3}B_p^2R^6\omega^4\sin^2\theta \end{aligned} \tag{1.2}$$

This energy carried away changes the kinetic energy producing a slow-down torque on the star given by

$$\mathrm{N} = I\dot{\omega}, \tag{1.3}$$

where **I** is the moment of inertia of the star. Using equation [1.2] and [1.3] one obtains an estimate of the magnetic field in terms of the period and the rate of change of the period of the star, which are measurable with high accuracy from the timing of the arriving pulses. Thus, the magnetic field is given by the expression (Manchester & Taylor, 1977)

$$B \sim (\frac{3Ic^3P\dot{P}}{8\pi^2R^6})^{1/2}, \tag{1.4}$$

where, P,$\dot{P}$ are the period and the period derivative, **I** is the moment of inertia and R is the radius of the star. There are problems with this simple model. Firstly, as far as the emission is concerned, this mechanism does not work in case of an aligned rotator. Refined theories dealing with the problem of emission for an aligned rotator have come into existence since then. And this simple estimate of the magnetic field

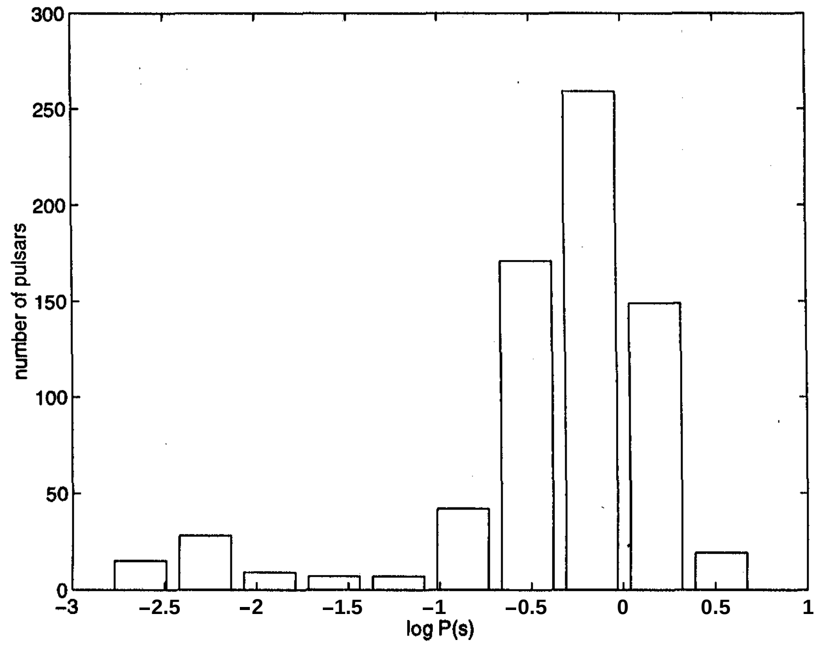

Figure 1.1: Histogram showing the period distribution of the radio pulsars.

provides a measure of the dipole component only, without any handle on the total field. Yet, this is still the most widely used and in most cases the only means of estimating the magnetic field. There have been a few direct measurements of the field, like that from the cyclotron line-strength of Her X-1, (Trümper et al., 1978) which gave the field strength of this neutron star to be $\sim 4 - 6 \times 10^{12}$ Gauss. But the scope of such direct measurement is limited only to the case of X-ray binaries. For radio pulsars no method for a direct measurement of the field exists.

With the discovery of a new variety of pulsar by Backer et al. (1982) another horizon in the pulsar research opened up. From now on the radio pulsars were divided into two distinct classes with very different physical characteristics. The new variety were named *millisecond pulsars* as these have very small rotation periods, in the range of milliseconds. The first one observed, PSR1937+21, had a period of 1.6 ms. Also they were found to have extremely short (compared to the earlier-observed *normal* pulsars) magnetic fields in the range of $10^8 - 10^9$ Gauss. In all some seven hundred pulsars have been observed to date. Figure [1.1] shows a histogram for the periods of all these pulsars. The period distribution is clearly bimodal, with most of the occupants of the peak at short periods being millisecond pulsars. One must admit here that the definition of millisecond pulsars is somewhat ad hoc, defined as the ones with spin periods less than $20ms$. Still the division serves quite well due to the fact that these two sets, as far

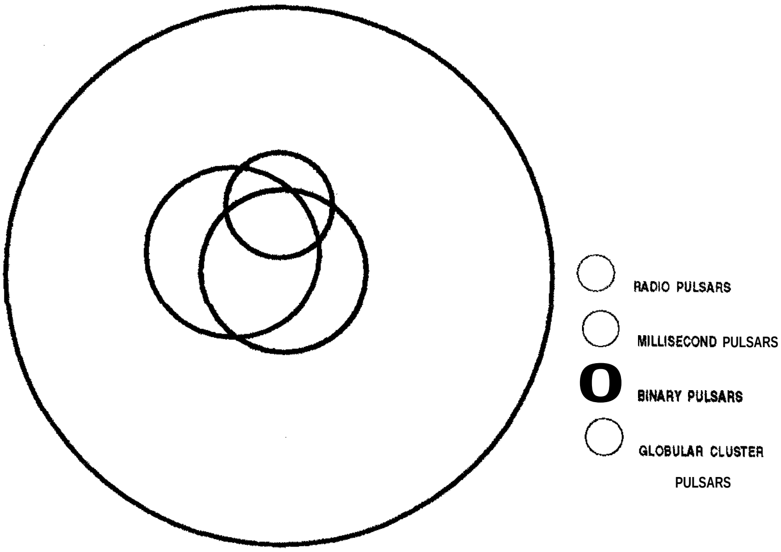

Figure 1.2: A schematic description of how the various special types of radio pulsars overlap with each other.

as present understanding goes, do have very different past histories. We make a crude comparison of these two classes of pulsars here in order to highlight the differences.

properties	**normal pulsars**	**millisecond pulsars**
spin period	$P \gtrsim 20$ ms	$P \lesssim 20$ ms
magnetic field	$10^{11} - 10^{13}$ Gauss	$10^{8} - 10^{9}$ Gauss
age	$\gtrsim 10^{6} - 10^{7}$ yrs	$\sim 10^{9}$ yrs
binarity	mostly isolated	mostly in binaries

The most striking difference is, of course, the fact that whereas the normal pulsars are mostly isolated, some 90% of the disk population and about 50% of the Globular Cluster population of the millisecond pulsars are in binaries. The age determination of some of the millisecond pulsars are possible also due to that fact. From the surface temperature of the white dwarf companion it has been possible to put a lower limit to the age of a few millisecond pulsars which lies in the range of 10^9 years (Callanan et

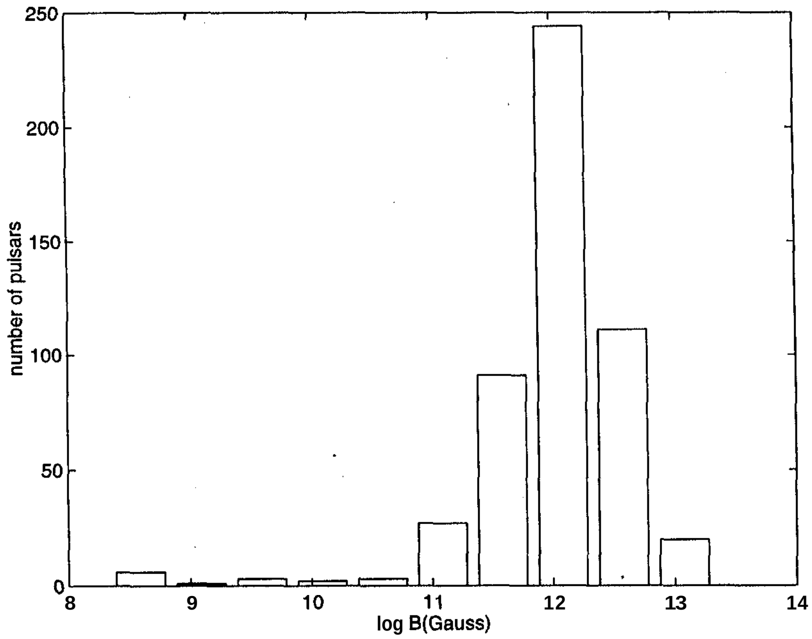

Figure 1.3: Histogram showing the distribution of the magnetic field in solitary radio pulsars.

al. 1989, Kulkarni, Djorgovski & Klemola 1990). On the other hand, in the case of normal pulsars it is basically the spin-down age estimated from the rate of change of the period which turn out to be a few million years at most. To emphasize the remarkable binary-millisecond pulsar association we draw here a Venn-diagram in figure [1.2] showing the nature of the pulsars, their binary association and the population (disk or globular cluster) to which they belong.

It has been observed that, in general, the binary pulsars have lower fields than the isolated pulsars. In figures [1.3] and [1.4] we have plotted the histograms of the field strengths of in these two categories separately.This fact was evident even in the first binary pulsar to be discovered, the famous PSR1913+16 discovered by Hulse & Taylor (1975). It was Bisnovatyi-Kogan & Komberg (1974) who suggested for the first time a connection between the decay of the magnetic field in a neutron star and its binary association. Taam & van den Heuvel (1986) provided observational support to this idea. In the early eighties the idea of *recycled pulsars* was forwarded in this connection (Srinivasan & van den Heuvel 1980, Radhakrishnan & Srinivasan 1982, Alpar, Cheng, Ruderman & Shaham 1982). According to this scenario an otherwise *normal* pulsar, at the end of its normal lifetime, could be resurrected with a reduced magnetic field and a spun-up period if it is processed in a binary. One of the problems faced by the theory of *recycled pulsars* is that of explaining the isolated low-field and millisecond

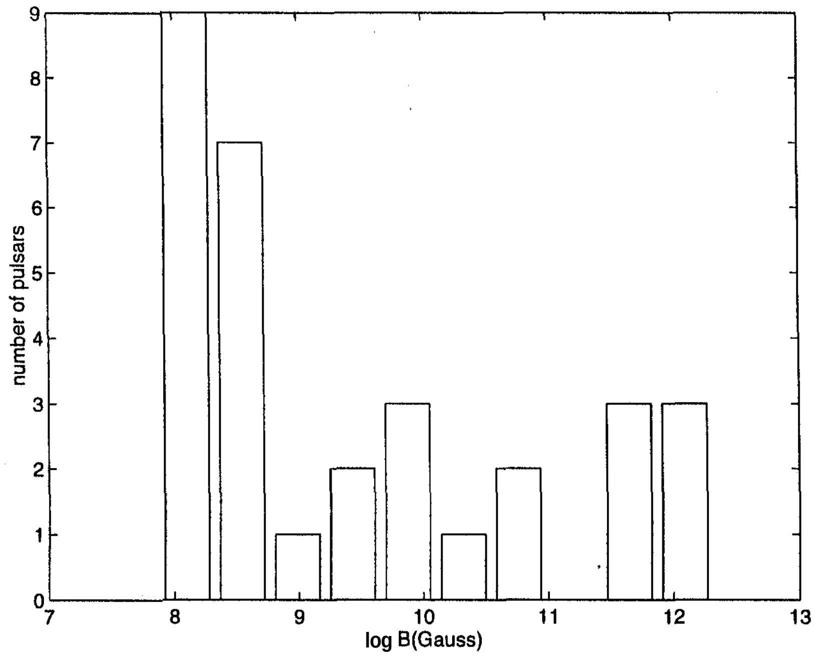

Figure 1.4: Histogram showing the distribution of the magnetic field in binary radio pulsars.

pulsars. Ruderman, Shaham & Tavani (1989) suggested that the companion could perhaps be ablated by the intense radiation falling on it from the pulsar. Soon afterwards PSR1957+20 (another 1.6 ms pulsar) was caught in the act of vaporising its companion (Fruchter, Stinebring & Taylor 1988). So that immediately confirmed this conjecture, although later on doubts have been raised regarding the efficacy of this method to completely destroy the companion. Yet, the connection between a reduction of the field strength and a binary history has remained well endorsed by observations. Though the theory of 'recycling' has its problems, to date this has been the most successful in explaining the population of the low-field and millisecond pulsars by integrating them with the class of normal pulsars through their binary history.

In order to develop a proper theory of the evolution of the magnetic field it is essential to understand the nature of the internal current configuration supporting the observed field. This also requires an accurate knowledge of the internal structure of the neutron stars which determines the long-term behaviour of the embedded current loops and hence the time-evolution of the magnetic field. Roughly, the neutron star has two physically different regions - the crust and the core. The crust is the outer shell, about a kilometer thick, which is a crystalline solid made up of neutron rich nuclei. In this region the density changes by some eight orders of magnitude, going from $10^6\ \mathrm{g\,cm^{-3}}$ at the very surface, to $10^{14.5}\ \mathrm{g\,cm^{-3}}$ at the boundary of the crust and the core (Pandharipande, Pines & Smith 1976). Underneath this crust lies the region with an average density of nuclear density or more, which is believed to have superfluid neutrons along with superconducting protons and extremely relativistic, Fermi degenerate electrons (Lattimer 1992, Pines & Alpar 1992). There is a lot of controversy about the exact composition of the core, opinions ranging from normal n-p-e plasma to exotic quark-condensates (Hanawa 1992, Lattimer, Pethick, Prakash & Haensel 1991, Pethick 1992, Prakash 1994, Tatsumi & Muto 1992 (and references therein)), but the above-mentioned picture is what is generally accepted at present.

Regarding the generation of the magnetic field in the neutron stars, there are two possibilities. The field could be a fossil field. The original magnetic field of the progenitor of the neutron star could be enhanced to large values by flux conservation during compactification of the large star to neutron star dimensions. As one believes the core to become superfluid soon after formation and in particular the protons form a type II superconductor, the field would be supported by the proton superconducting flux tubes in this case. But there are problems with this scenario. Firstly, there are no good measurements for the core field of the massive stars, so it is not certain whether the field strength required to enhance it to the pulsars field values really obtain in the progenitor core. On the other hand, in an extremely violent process like a supernova explosion, whether an adiabatic process like flux conservation would hold good is not clearly understood. The other possibility is that of the generation of the field after the birth of the neutron star. Blandford, Applegate & Hernquist (1983) pointed out that it is possible to generate a field in the crust of a cooling neutron star due to thermomagnetic instabilities as the heat flows in presence of a seed field. This mechanism, again, suffers from the fact that a seed field of the order of 10^8 Gauss is required in order to produce the canonical field values that are observed in neutron stars. Though none of the theories are free from hitches, for want of better alternatives, these are accepted as the best possibilities for the origin of the field in neutron stars.

It is, of course, obvious that the evolution of the field would itself depend on the generation mechanism, which determines the underlying configuration of currents. Initially, observational data appeared to indicate that the pulsar magnetic fields decay with a time constant of $\sim 10^6$ years (Gunn & Ostriker 1970; Lyne, Anderson & Salter 1982). On the other hand, it was shown by Baym, Pethick & Pines (1969) that given the state of matter in a neutron star the electrical conductivity is expected to be extremely high and the ohmic dissipation time-scale should be larger than the Hubble time. It was borne out by some recent statistical work (Bhattacharya et al. 1992, Hartman et al. 1997), where they showed that the magnetic field of the isolated pulsars indeed do not show any significant decay. An investigation of the association of the field decay and a binary history therefore becomes extremely pertinent. In the past few years a considerable amount of effort has been spent in trying to find the answer to this question (for details see Bhattacharya & Srinivasan 1995 and references therein). The basic understanding in this regard could be divided into two classes. The underlying physics of the field evolution in a binary is that of the ohmic dissipation of the current loops in the accretion-heated crust. Therefore, for the believers in crustal field, the current dissipates due to an increase in temperature as mass is accreted by the neutron star from its companion in the course of binary evolution. When one assumes an initial core field configuration, a phase of spin-down driven flux-expulsion is necessary prior to the phase of the ohmic dissipation in the crust. Both these ideas have been explored in detail by a multitude of researchers (for a review see Bhattacharya, 1995a) yet by no means have all the questions been answered.

Therefore, fifteen years after the discovery of the millisecond pulsars there still remains a lot of uncertainties regarding their possible past history. On a broader perspective the scenarios for both the generation and the evolution of magnetic fields of neutron stars lack a consensus. A coherent theoretical picture is yet to emerge. In such a situation, the observational data is the only guide. In this thesis, therefore, we have tried to address a few questions related to the evolution of the magnetic field of neutron stars that are members of binary systems. We try to make connection with the overall picture of the field evolution as indicated by observational data. In particular we look into the problem of the generation of millisecond pulsar from particular kind of binary systems. To this end we have looked at four related problems as described below :

- the effect of diamagnetic screening on the final field of a neutron star accreting material from its binary companion;
- evolution of magnetic flux located in the crust of an accreting neutron star;
- application of the above-mentioned model to real systems and a comparison with observations;
- an investigation into the consequences of magnetic flux being initially located in the core of the star and its observational implications.

Here then is a brief resume of the problems mentioned above.

1. The effect of diamagnetic screening - The basic idea is that the magnetic field is screened due to the stream of the accreting material that arrives at the polar cap, being channeled by the strong magnetic field of the star. A screening of the external dipole field, in this case, is achieved by the production of horizontal components at the cost of poloidal ones. If fluid-interchange instabilities are ignored then the field lines are frozen to the material (since the flow time-scales are very much smaller than the diffusive time-scales) and as the accreted material spreads over the surface it drags the field lines along. The field lines would then reconnect on the equatorial plane and get buried. Before this field can diffuse out more matter will come and spread on top of it, and push the field to even deeper regions. Finally the field may even reach the Superconducting core from where it will not diffuse out. But whether such burial is at all possible depends on the relative magnitude of the time-scales of flow, diffusidn and interchange instability. This question has already been addressed before, and the calculations made by us re-assert the fact that the fluid-interchange time-scales are too small for the burial of the field to be effective since any stretching of the field lines is quickly restored over this overturn time-scale. Therefore the cause of the low field observed in some neutron stars in X-ray binaries or in millisecond pulsars can not be due to a simple screening of their magnetic field by the accreted matter.

2. Evolution of a crustal magnetic flux under accretion - This investigation is carried out assuming the underlying currents, supporting the observed field, to be entirely confined to the crust of the neutron star to start with. The main mechanism responsible for the field decay here is the ohmic dissipation of the current loops in the accretion-heated crust. The evolution is investigated for a wide range of values of the relevant physical parameters, such as the rate of accretion, the depth of current carrying layers etc. We find that within a reasonable range of parameter values final fields in the correct range for millisecond pulsars are produced. A most important feature has been seen to arise due to the inward material movement of the crustal layers because of accreted overburden. The current loops reach the region of very high conductivity in the deeper and denser regions of the star by such material movement and this puts a stop to further field decay. This **freezing** in behaviour that comes naturally out of the input physics, is very important in explaining the limiting field values observed in binary and millisecond pulsars. Therefore, within the limits of uncertainty this model, besides providing for an effective mechanism for field reduction by the right order of magnitude, also gives

an explanation for the lower bound of the field observed in millisecond pulsars.

3. Comparison with observations - Here we investigate the evolution of the magnetic field of neutron stars in its entirety – in case of the isolated pulsars as well as in different kinds of binary systems, assuming the field to be originally confined in the crust. A comparison of our results for the field evolution in isolated neutron stars with observational data helps us constrain the physical parameters of the crust. We also model the full evolution of a neutron star in a binary system through several stages of interaction. Initially there is no interaction between the components of the binary and the evolution of the neutron star is similar to that of an isolated one. It then interacts with the stellar wind of the companion and finally a phase of heavy mass transfer ensues through Roche-lobe overflow. We model the field evolution through all these stages and compare the resulting final field strength with that observed in neutron stars in various types of binary systems. One of the interesting aspects of our result is a positive correlation between the rate of accretion and the final field strength. Recently there has been observational indications for such a correlation. Our results also match with the overall picture of the field evolution in neutron stars. In particular, the generation of millisecond pulsars from low-mass binaries arises as a natural consequence of the general framework.

4. Lastly, we look at the outcome of spindown-induced expulsion of magnetic flux originally confined to the core, in which case the expelled flux undergoes ohmic decay. We model this decay of the expelled flux. Once again we look into the nature of field evolution – both for neutron stars that are isolated and are members of binary systems. This scenario of field evolution could also explain the observed field strength of neutron stars but only if the crustal lattice contains a large amount of impurity. At present both the scenarios (assuming an original crustal field and an expelled flux) appear to be consistent with the observations though they require rather different assumptions regarding the state of the matter in the crusts of the neutron stars. Also, the detailed predictions in the two scenarios are different. Therefore future observations, able to pin down these details, should distinguish between the two models. On the other hand, with an unambiguous determination of the state of the matter in the neutron star crust, at some future date, it will again be possible to arrive at a definitive conclusion regarding the model of field evolution that actually prevails in neutron stars.

Improved observational techniques have produced a wealth of data in the recent past which requires an accurate and detailed understanding of pulsar physics. Unfortunately, the regime in which the physical theories are lacking are precisely the regimes in which the neutron stars are the only available systems. And the data, though enormous, still remain inadequate for answering such questions unambiguously. The handicap is many-faceted, like the uncertainty in the form of a nucleon-nucleon interaction potential or the inadequacy of the quantum many body techniques to handle the nuclear density systems. Even though the basic picture of field reduction via ohmic dissipation is on secure grounds there are still many uncertainties, for example due to uncertainties in :

- the crustal structure, in particular regarding the exact forms of the nuclei,
- the transport properties arising due to a lack of proper knowledge of the impurity concentration or the dislocations that exist in the crust,
- the change in the composition due to accretion, since the newly-formed accreted crust do not contain cold-catalysed matter like the original crust, or
- the thermal behaviour in both isolated and accreting neutron star.

As for the generation of the millisecond pulsars, quite apart from the birthrate problem, all the model calculations also suffer from uncertainties in the binary evolution.

If the physics of these are understood a lot of accepted wisdom may change. Refined many-body calculations of proton superconductivity has already cast doubts on the magnetic field being supported by the fluxoids threading the core (Ainsworth, Wambach, Pines 1989). Therefore to understand the basic problems at least within the standard premises one needs to have a second look at the problems incorporating all the new refinements that have been coming in. That seems to be the next logical step. On a different level, new and exotic physics is making inroads like the Strange stars being put forward as possible pulsar candidates (Cheng & Dai 1997). Those probably would start the new era of pulsar research.

This thesis has been organized as follows. In chapter 2, we review the basics of neutron star physics, aspects that we have needed for our calculations. Chapter **3** discusses the standard scenario for the generation and evolution of neutron star magnetic fields. In chapters 4 to 7 we describe the details of the four problems that have been worked on. Finally in chapter 8 we have made our conclusions along with a discussion of the uncertainties inherent in these investigations and the possible future directions of work along these lines.