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Evolution of Neutron Star Magnetic Fields

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Abstract. This paper reviews the current status of the theoretical models of the evolution of the magnetic fields of neutron stars other than magnetars. It appears that the magnetic fields of neutron stars decay significantly only if they are in binary systems. Three major physical models for this, namely spindown-induced flux expulsion, ohmic evolution of crustal field and diamagnetic screening of the field by accreted plasma, are reviewed.

Key words. Neutron stars—Magnetic field.

1. Introduction

Neutron stars are strongly magnetised objects, with the surface field strength ranging from $\sim 10^8$ to 10^{13} G, as inferred from radio pulsars, accreting X-ray pulsars and low-mass X-ray binaries. There also exists another class of objects, consisting of anomalous X-ray pulsars and soft gamma repeaters, often referred to under the umbrella term "magnetars", in which the magnetic field of the underlying neutron stars probably approaches $\sim 10^{15}$ G. In this lecture I shall address the issue of the evolution of the magnetic fields of neutron stars of the first variety. At field strengths as high as those for magnetars, a different physics operates to determine field evolution (see Thompson 2000), which will be beyond the scope of this brief review.

It is now an established fact that among radio pulsars the isolated objects primarily have their magnetic field strengths clustered around 10^{12} G, and significantly lower field strengths are mainly associated with pulsars in binary systems. While it was once thought that pulsars in binary systems have lower field strengths simply by virtue of their larger age, detailed analyses of the radio pulsar population have failed to find evidence of spontaneous field decay in isolated objects (Bhattacharya *et al.* 1992; Mukherjee and Kembhavi 1997; Lorimer *et al.* 1997). The currently preferred view, therefore, is that processing of neutron stars in binary systems affect their magnetic field strength.

The magnetic field of a neutron star determines the evolution of its spin, its radiative properties and its interaction with the surrounding medium. The evolution of the magnetic field is therefore a key component in the evolution of the neutron star as a whole, but it remains to be clearly understood. In the following sections I shall review our current, relatively incomplete, understanding of the magnetic field evolution.

2. Location of the field

A neutron star has two distinct regions in its structure:

- A core, constituting the bulk of the star, where the density is above nuclear matter density. In this region the neutrons (∼99%) and protons (∼ 1%) are not bound in nuclei. The neutrons are expected to form a ^3P superfluid and the protons a ^1S superconductor (Sauls 1989).
- A crust overlying the core. Here the density gradient is sharp, rising from a few g/cm^3 at the surface to nuclear density (3×10^{14} g/cm^3) within ∼10% of the stellar radius. The protons in the crust are bound in nuclei that get progressively neutron rich as density rises. At densities above 4×10^{11} g/cm^3 free neutrons appear, and co-exist with nuclei until nuclear density is reached. The nuclei in the crust are expected to form a lattice; the electrons are free and highly degenerate, resulting in metal-like transport properties (electrical and heat conductivities) in this region (Yakovlev & Urpin 1980).

We have no *a priori* knowledge of the distribution of the magnetic field in the interior of the neutron star. This would be determined by the process that generated the magnetic field in the first place. In the simplest scenario, that of flux-freezing from the progenitor, the field would most likely be distributed throughout the interior. However, in some other scenarios, e.g., the thermo-magnetic battery effect (Blandford *et al.* 1983), most of the magnetic field will be confined to the crust.

The evolution of the magnetic field in these different cases is expected to be different. Observation of the long-term evolution of the magnetic field could therefore in principle be used to put constraints on the location of the field in the neutron star interior. However the subject is still too premature to realise this in practice.

In either model of the location of the magnetic field, changes in the field strength could be expected both due to spontaneous evolution and due to accretion. A physical model of field evolution should satisfy the observational constraints that relatively little magnetic field decay should take place in isolated radio pulsar population (dominated by neutron stars in the age range 10^5–10^7 years), while accretion should be able to reduce the surface field strength by several orders of magnitude.

3. Mechanisms of field evolution

The simplest possible cause for field decay would be ohmic dissipation. Conductivities low enough for this to be important are encountered only in the outer parts of the crust in an isolated, cooling neutron star. If the neutron star is accreting, however, the resulting increase in crustal temperature and the consequent reduction of conductivity could be important for most of the crust.

If the magnetic flux is originally located in the superconducting interior, it has to be first expelled to the crust before any decay can occur. A mechanism for this was suggested by Srinivasan *et al.* (1990): In the core of the neutron star the protons are expected to form a Type II superconductor, which can carry magnetic flux in quantized fluxoids. Although the magnetic field here is probably less than the lower critical field, estimated to be of order 10^{15} G, the flux is nevertheless thought to be trapped in fluxoids in a metastable state. The reason for this is that the electrons, which also permeate this region, form an extremely highly conducting normal fluid, making it impossible to expel the flux from this region in the time scale of nucleation of superconductivity in the initial few months after the formation of the neutron star (see Sauls 1989 for a review). The rotation of the neutron star causes vortices in the neutron superfluid co-existing with the proton superconductor. Pinning and electromagnetic interaction are expected to exist between the neutron vortices and proton fluxoids, causing the fluxoids to be dragged out to the crust as the star spins down and vortices are expelled (Srinivasan *et al.* 1990, Bhattacharya & Srinivasan 1995).

Just the expulsion of the magnetic flux from the core still does not imply a change in the field strength of the star as experienced by an external observer. The expelled field must then decay due to ohmic processes for this to happen. If the crust is made of pure cold catalysed matter annealed into a perfect crystalline state, the conductivity of the inner crust is much too high for the flux deposited at the bottom of the crust to evolve appreciably in a Hubble time. A significant impurity concentration in the crust and/or a turbulent Hall cascade (creating small scale current loops) must be invoked to bring the effective ohmic time scale down to interesting values (Goldreich & Reisenegger 1992; Bhattacharya & Datta 1996).

Yet another possible way to reduce the magnetic field strength felt outside the star is to screen the field away by accreting matter (e.g., Bisnovatyi-Kogan & Komberg 1974). As the highly conducting accreting plasma settles and spreads onto the surface of the neutron star, it could produce a diamagnetic screening effect, burying the stellar field underneath it. This mechanism would not depend on the location of the field in the stellar interior.

4. Recent results

4.1 *Core field*

The vortex-fluxoid coupling model has been developed considerably since its first suggestion, and application to various classes of neutron stars has been explored in some detail. The most comprehensive work to date is by Jahan-Miri (2000), who finds that it is possible to reproduce the long-lived low magnetic field strengths of most binary pulsars, assuming a decay time of $\sim 10^7$ yr for the expelled field, and a rather efficient spin-down of the neutron star during the “propeller phase” of accretion, when the accreting plasma is expelled from the magnetosphere, extracting angular momentum from the spinning neutron star via magnetic coupling. The shorter the decay time scale of the expelled field, the quicker the propeller phase ends, limiting the total amount of flux expulsion from the interior. Decay time scales as short as 10^7 yr are, however, somewhat difficult to reconcile with some of the accreting X-ray pulsars in massive binary systems where fields of order 10^{12} G appear to survive, as well as with the population of isolated pulsars if most pulsars are born with spin periods much less than a second (Bhattacharya *et al.* 1992; Jahan Miri & Bhattacharya 1994). It appears difficult in this model to reproduce the high residual magnetic fields in some recycled pulsars arising from low-mass X-ray binaries (e.g., 3×10^{11} G in PSR B0820+02).

Of late, some attempts have been made to model the feedback of the expelled and accumulated flux at the crust bottom on further flux expulsion. Konenkov & Geppert (2000), within a simplified model, estimate this feedback to be very strong for magnetic field strengths above $\sim 10^{11}$ G, and suggest that the spindown-induced flux expulsion would be very ineffective for neutron stars with original core field strengths above this value.

4.2 *Crustal field*

The evolution of the magnetic flux originally confined to the crust depends on the depth at which the bulk of the current distribution is located. This is because conductivity rises steeply with depth, nearly proportional to density in a pure matter crust. In the outer crust, conductivity depends significantly on the local temperature, while in the inner crust (at densities above $\sim 10^{13}$ g/cm^3) impurity scattering may dominate the resistivity mechanism.

A neutron star is born hot, and cools with time (unless accretion occurs on the surface). The conductivity of the outer crust therefore increases with time. Cooling rates of neutron stars have been computed under various assumptions, a useful compendium is found in Page (1998). Using a typical "standard" cooling curve for a neutron star, one finds that the magnetic field of an isolated neutron star would decay by some amount in the first $\sim 10^5$ yr, when the star is still relatively hot, and thereafter remain constant (cf. Urpin & Van Riper 1993). This field reduction could be about a factor of ~ 30 if the initial confinement depth of the field corresponds to a density $\rho \sim 10^{11}$ g/cm^3, whereas it would be only a factor of ~ 2 for a confinement density of $\sim 10^{13}$ g/cm^3. However, since most observed radio pulsars are older than $\sim 10^5$ yr, it is at present not possible to determine the extent of this early decay from observations (Tauris & Konar 2001).

Accretion onto the neutron star affects the evolution of the crustal field in two ways. First, the accretion process raises the crustal temperature and maintains it at a high level through the duration of accretion. Second, the accreted mass compresses the original crustal matter, raising the density of the current carrying layers. After the accretion of about $\sim 10^{-2} M_\odot$ the original crust would be assimilated into the core. While the heating of the crust hastens the ohmic decay, the compression and the consequent rise in local conductivity retards it, so the final result depends on the competition between these two processes. Detailed computations show the general nature of the field evolution to be that of a rapid initial decay followed by a "freezing", at a "residual" field strength determined by the original confinement depth and the accretion rate. The lower the accretion rate, the longer the initial decay lasts, resulting in a correlation between the residual field strength and the accretion rate (Konar & Bhattacharya 1997), as appears to have been found in some low-mass X-ray binaries (White & Zhang 1997).

This scenario of field evolution is able to reproduce many of the broad features of the magnetic field distribution of neutron stars (Urpin, Geppert & Konenkov 1998; Konar & Bhattacharya 1999). More detailed work still remains to be done to model individual observed cases. Nevertheless, this remains one of the attractive models of field evolution.

4.3 *Diamagnetic screening*

The idea that the accreting stream of plasma could screen the magnetic field of a neutron star as it settles down has been in the literature for a long time (Bisnovatyi-Kogan & Komberg 1974; Taam & van den Heuvel 1986; Romani 1990). However this problem is only now beginning to be addressed with some of the necessary microphysics. It turns out that the accretion flow in the polar cap of a magnetised neutron star is acutely susceptible to various magnetohydrodynamic instabilities and it is difficult to make even a qualitative assessment of the effectiveness of screening without a full three-dimensional computation which is yet to be attempted. One-dimensional plane-parallel models by Cumming, Zweibel & Bildsten (2001) suggest that the diamagnetic screening is ineffective for field strengths above $\sim 10^{10}$ G as well as for accretion rates below ~ 1 per cent of the local Eddington rate. For higher field strengths, magnetic buoyancy prevents screening, and at lower accretion rates the field can diffuse through the accreting matter.

A two-dimensional (azimuthally symmetric) model explored recently by Rai Choudhuri & Konar (2001) uses a self-consistent velocity field of the accreted matter as it sinks and joins the rest of the crust. They find that the screening does operate in their model, but in the presence of magnetic buoyancy the net reduction in field strength does not exceed about an order of magnitude.

The real three-dimensional situation may be qualitatively different, however. Instabilities leading to bunching of magnetic field lines, leaving relatively low-field regions for the accreting matter to spread through are a real possibility. Such instabilities will further reduce the degree of diamagnetic screening that can be achieved. One needs to make realistic MHD simulations to address this possibility.

5. Conclusions

A successful model of the origin and evolution of the magnetic field of neutron stars should provide a natural explanation for the following basic observational facts:

- the range $\sim 10^{12}$ to $\sim 10^{15}$ G of the field strengths of young neutron stars,
- the relative stability of the field strength of isolated pulsars in the time scale of $\geq 10^8$ years, perhaps with a small reduction by less than an order of magnitude,
- the reduced magnetic fields in neutron stars processed in binaries,
- on an average, larger field reduction in products of low-mass X-ray binaries than those of high-mass X-ray binaries,
- evidence, from cyclotron lines, of strong ($\sim 10^{12}$ G) magnetic fields in several *accreting* X-ray binaries and
- apparent correlation between luminosity and magnetic field in low-mass X-ray binaries.

Clearly, none of the models presented above addresses all of these issues. On the whole, at present the ohmic evolution of crustal field appears to be somewhat more successful than the others. However several mechanisms, such as the diamagnetic screening by accreted matter as well as Hall effect-driven evolution are only now beginning to be explored in quantitative detail, and will hopefully be able to contribute to a better understanding of the field evolution.

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