Part II

Evolution of the magnetic field

Monday afternoon. Session Chair: Leon Mestel

- What is the structure and orientation of the pulsar magnetic field?
    - ⋆ Evolution of the magnetic field
        - ∗ Factors influencing the formation and orientation of the original magnetic field.
        - ∗ Physical models of the pulsar magnetosphere for near-vacuum conditions.
        - ∗ Observations bearing on magnetic field decay and alignment/counter-alignment.
        - ∗ Physical considerations pertaining to the electrical conductivity of neutron stars.
        - ∗ Observations and physical considerations pertaining to the possibility of precession.

The second session of the Colloquium was opened by a review paper, entitled, The evolution of the magnetic fields of neutron stars, *presented by Dr. Dipankar Bhattacharya. We note that after the Colloquium Dr. Bhattacharya and Dr. E. P. J. van den Heuvel published a much longer paper entitled* Formation and evolution of binary and millisecond radio pulsars (Bhattacharya and van den Heuvel 1991).

THE EVOLUTION OF THE MAGNETIC FIELDS OF NEUTRON STARS

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Abstract

The evolution of the magnetic field strength plays a major role in the life history of a neutron star. In this article the observational evidence of field evolution, in particular that of field decay and magnetic alignment, are critically examined. It is concluded that the observed decay of the spindown torque on radio pulsars cannot be caused by a secular evolution of the "obliqueness" of the neutron star, as suggested by some authors. Recent observations provide a strong indication that the decay of the magnetic field strength of a neutron star may be closely related to its evolution in a binary system. Theoretical models for such an evolution are discussed.

Introduction

Neutron stars are among the most strongly magnetized objects known in nature. The origin and evolution of this huge magnetic field has been a subject of considerable interest and debate ever since the discovery of pulsars. The discovery of several binary and millisecond pulsars in the last few years has generated a fresh wave of interest in this subject, in view of the role the magnetic field plays in the spin evolution of neutron stars, especially in a binary system. The aim of the present article is to summarize our current understanding of the evolution of the magnetic field of neutron stars based on the recent observational evidence and related theoretical developments.

Our knowledge of the magnetic fields of neutron stars comes mainly from radio pulsars with measured spindown rates. With the assumption that the spindown torque on a pulsar equals that due to magnetic dipole radiation on an orthogonal rotator, the observed spin period P and the spindown rate $\dot{P}$ can be combined to yield a measure of the average strength of the dipole field at the neutron star surface (Pacini 1967, Ostriker and Gunn 1969, Manchester and Taylor 1977):

$$B_s = \left(\frac{3c^3 I P \dot{P}}{8\pi^2 R^6} \right)^{1/2} \simeq 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ Gauss} \qquad (1)$$

where $I \simeq 10^{45}\,\mathrm{g\,cm^2}$ is the moment of inertia of the neutron star and $R \simeq 10^6$ cm its radius. Eq. (1) yields $B_s \sim 10^{12} - 10^{14}$ Gauss for most radio pulsars.

A class of neutron stars in accreting binary systems show regular X-ray pulsations. These are believed to have field strengths $\gtrsim 10^{10}$ Gauss, needed to sufficiently collimate the accretion flow onto the magnetic poles. The spin periods of these neutron stars, as well as their spin-up/spin-down rates also indicate magnetic fields $\sim 10^{11}$–10^{12} Gauss (see, *e.g.* Nagase 1989).

In addition to this, it has also been possible to detect cyclotron absorption lines in the X-ray spectra of a few accreting neutron stars, including some γ-ray bursters (Trümper *et al.* 1978, Murakami *et al.* 1988). These lines suggest field strengths of order 10^{12} Gauss in these neutron stars. It must, however, be borne in mind that the spindown of a radio pulsar and the collimation of the accretion flow in an X-ray binary depend mainly on the ***dipole component*** of the magnetic field, while the cyclotron absorption lines measure the ***total*** field strength in the absorption region which, near the stellar surface, ***may*** be dominated by multipole components.

The origin of the magnetic field

Regarding the origin of neutron star magnetic fields, there are two schools of thought: one which believes that these strong fields are inherited from their progenitors, and amplified during the collapse to the neutron star phase, and the other which contends that these fields are generated after the neutron star is born.

The fact that flux conservation during collapse may lead to a strong field in a neutron star was pointed out even before pulsars were discovered (Woltjer 1964). It has also been argued that such a field need not be a remnant of the stellar field in the main-sequence phase, but is built up during a convective carbon-burning phase just before the collapse occurs (Ruderman and Sutherland 1973).

More recently, it has been suggested (Blandford, Applegate, and Hernquist 1983) that magnetic fields in neutron stars may be generated by a thermally-driven battery process after the star is born. So far, there is no clear observational evidence that this actually takes place (see, *e.g.* Bhattacharya 1990b). The available constraints from the observed properties of a few young pulsars suggest that most of the field generation should occur within a few hundred years after the neutron star is born (Bhattacharya and Shukre 1985, Bhattacharya 1987, Bhattacharya 1990b), in which case it becomes observationally almost indistinguishable from any fields present right since birth. It is, however, important to realize that the later evolution of the magnetic field is likely to depend on its actual origin. If the magnetic field is a fossil remnant of that of the progenitor star, then the flux is expected to thread the superconducting region in the stellar interior, and thus be carried by superconducting proton vortices. The long-term evolution of such a magnetic field would be then determined by the properties of the neutron-star interior and also by those of the crust. The thermally generated magnetic flux, on the other hand, is expected to be confined to the crustal region, and its long-term evolution will be determined by the properties of the crust alone.

Magnetic field decay

One of the oldest, and most persistent ideas about the evolution of the magnetic field of a neutron star is that it decreases with age. There are several indications for this. For example, a young pulsar associated with a supernova remnant has a higher magnetic field than an old one associated with a globular cluster or a very cool white dwarf companion. Also, the high magnetic field, pulsating X-ray sources have young, massive mass-donating stars, while the non-pulsing X-ray sources are associated with old, low-mass donors.

The suggestion that the magnetic fields of pulsars may decay with age was made soon after the discovery of pulsars. Based on early estimates of the conductivity of a neutron star Ostriker and Gunn (1969) suggested that their magnetic field should decay exponentially with a timescale $t_\mathrm{d} \sim 4\times10^6$ yr, because of ohmic dissipation of the supporting currents. However, it was soon argued by Baym *et al.* (1969) that the interior of a neutron star is likely to be superconducting and the ohmic decay of the magnetic field cannot be important. Gunn and Ostriker (1970), on the other hand, presented observational evidence in favor of field decay: They plotted the magnetic fields derived from eq.(1) against the "spindown age" τ ($\equiv P/2\dot{P}$) of ~15 pulsars for which the spindown rates were known at that time. The plot showed a clear decrease in derived B_s with increasing τ. But, as pointed out by Lyne *et al.* (1975), such arguments for field decay are extremely unreliable, since most of the above trend is artificial, caused by a much larger range in $\dot{P}$ than in P of the observed pulsars.

A more persuasive argument for field decay came with the measurement of the velocities of radio pulsars (Lyne, Ritchings, and Smith 1975, Helfand and Tademaru 1977, Lyne, Anderson, and Salter 1982, Lyne, Manchester, and Taylor 1985). The velocity transverse to the line of sight has now been measured for over 75 pulsars (Lyne, Anderson, and Salter 1982, Cordes 1986, Bailes *et al.* 1989, Bailes *et al.* 1990), and these clearly indicate that pulsars are high-velocity objects, with a population average speed of ~200 km s^{-1}. As a result they are able to migrate to large distances from the plane of our galaxy despite being born very close to it. Thus the distance z of a pulsar from the mean galactic plane can in fact be used as an indicator of its age. Comparing the "kinetic age" t_k, defined as the ratio of the z-distance and the z-velocity, and the spindown age τ of 13 pulsars (figure 1), Lyne *et al.* (1982) came to the conclusion that for $\tau \lesssim 2\times10^6$ yr the spindown age provides a reasonable estimate of the true age of the pulsar, but beyond this the spindown age quickly becomes a gross overestimate of the true age, exactly as would be expected from a decay of the field strength. If the field strength B_s decreases exponentially, *i.e.* $B_\mathrm{s} = B_\mathrm{s}(t=0)\exp(-t/t_\mathrm{d})$, then the spindown age increases as

$$\tau = \left(\tau_0 + \frac{t_\mathrm{d}}{2}\right)\exp(2t/t_\mathrm{d}) - \frac{t_\mathrm{d}}{2}. \qquad (2)$$

According to eq.(2) τ scales linearly with time for $t \ll t_\mathrm{d}$, but shows an exponential increase for $t \gtrsim t_\mathrm{d}$.

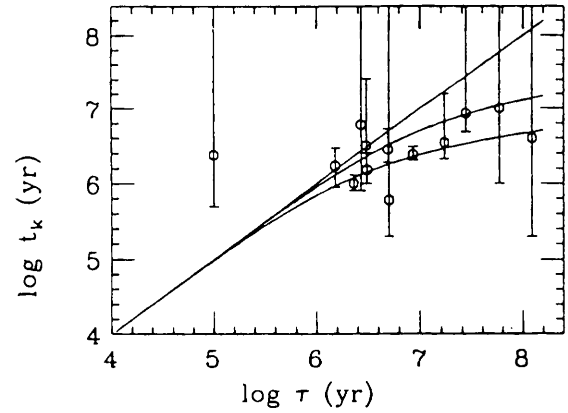

Figure 1 Observed relation between the kinetic ages and the spindown ages of 13 pulsars from Lyne, Anderson and Salter (1982). The three curves correspond to (from top) the expected relation in case of no field decay, and an exponential decay with timescales of 8 Myr and 2 Myr respectively.

Fitting this to the observed data a decay timescale t_d in the range 2–10 Myr was obtained (Lyne, Anderson, and Salter 1982, Lyne, Manchester, and Taylor 1985), but the large uncertainties in t_k introduced by the unknown radial components of the velocities and the unknown location of a pulsar's birthplace weakens this result to some extent. A similar conclusion can be arrived at from the observed z-distribution of pulsars. Figure 2 shows the average z-values of 7 groups of 50 pulsars each in different bins of τ. As can be clearly seen, the distribution is confined to within $z \sim 500$ pc. This, along with the observed population average velocity of $\sim$200 km s^{-1} suggests that most pulsars are $\lesssim$5 Myr old. The spindown ages, on the other hand, extend more than an order of magnitude beyond this value—up to $\sim 10^8$ yr. Evidently the spindown ages increase faster than the true age. In figure 2 the effect of an exponential field decay is also shown. While the z-distribution expected with no field decay (dashed line) is a very poor fit to the observations, that including an exponential decay of the field strength (solid line) resembles the data much more closely.

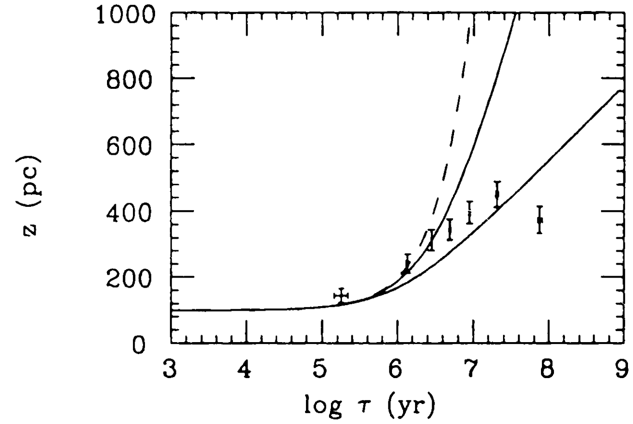

Figure 2 The average distance from the galactic plane of 7 groups of 50 pulsars each, arranged according to their spindown ages. The error bars correspond to $\pm 1\sigma$ errors on the mean values. The dashed curve shows the expected distribution for no field decay and a population-average space velocity of 170 km s^{-1}. The solid lines include exponential field decay with timescales of 8 Myr and 2 Myr, respectively.

Alignment *vs.* field decay

Strictly speaking, however, what the discrepancy between the kinetic age and the spindown age of pulsars shows is a decay of the spindown torque on the pulsar, which we have interpreted as a decay of the magnetic field strength. According to the critics of the field decay hypothesis (Kundt 1981, Kundt 1988, Candy and Blair 1983, Candy and Blair 1986, Blair and Candy 1989, Beskin, Gurevich, and Istomin 1984), the spindown torque may decrease due to reasons other than field decay. For example, if the spindown process is dominated by the magnetic dipole radiation from the pulsar (see above) then the spindown torque is given by:

$$N = I\dot{\Omega} = \frac{2}{3c^3} B_s^2 R^6 \Omega^3 \sin^2 \alpha \qquad (3)$$

where Ω is the angular velocity of the star, α the obliqueness, and the other symbols have their usual meaning. If, during the course of evolution, the obliqueness α is reduced (*i.e.* the spin axis of the pulsar tends to "align" with the magnetic axis), it will result in a decrease of the spindown torque even though the field strength B_s remains constant.

It has, in fact, been pointed out by several authors (Ostriker and Gunn 1969, Davis and Goldstein 1970, Michel and Goldwire 1970, Goldreich 1970) that if a magnetized sphere with a pure dipole exterior field spins in vacuum, there is a component of the torque on the neutron star which tends to align the spin axis with the magnetic dipole. Gunn and Ostriker (1970), however, preferred to interpret the torque decay as a decay of the field strength, because the alignment torque depends critically on the magnetospheric structure: it can be suppressed by a slight departure of the magnetic field geometry from a pure dipole, or may even be reversed (tending to drive the star towards orthogonality) if the torques due to magnetospheric currents dominate the spindown process (Good and Ng 1970).

While a decay of the field strength remains the most favored explanation for the torque decay, several authors (Kundt 1981, Candy and Blair 1983, Blair and Candy 1989) have suggested an exponential decay of $\sin\alpha$ as a possible alternative reason. Indeed, from the point of view of the observations discussed above, this would be indistinguishable from an exponential decay of the field strength. Fortunately, over the past couple of years new data has become available which makes it possible for the first time to distinguish between these two alternatives.

This new data set consists of the estimated values of the obliqueness α of $\sim$150 pulsars—about 100 of them obtained by Lyne and Manchester (1988) from the "conal" components of emission, and another $\sim$100 by Rankin (1990) from the "core" components. About 50 pulsars are common to the two samples and, despite systematic differences in a small number of cases, the general agreement between the α-values derived using the two independent methods is remarkably good.

These measurements of α can be used (Srinivasan 1989, Bhattacharya 1989) to test the hypothesis that the observed decay of the spindown torque occurs due to alignment rather than field decay. Figure 3 shows a scatter diagram of α *vs.* spindown age of these pulsars, with the expected upper envelopes of the distribution for three different values of the alignment timescale t_a: 10^7, 10^8 and 10^9 yr. These curves assume a vacuum-dipole spindown torque (3), a constant field strength B_s, and $\sin\alpha$ decreasing exponentially (Blair and Candy 1989, Candy and Blair 1983): $\sin\alpha = \sin\alpha(0)\exp(-t/t_a)$. As can be seen from the figure, the upper envelope of the distribution is described better, if at all, by the 10^8 yr line. This clearly indicates that alignment cannot cause torque decay in the timescale of a few million years—unless the torque decreases much more quickly with α than in the vacuum-dipole model given by eq.(3). The dependence of the spindown torque on α can also be tested using the same data set. For this purpose we may generalize the expression for the spindown torque as:

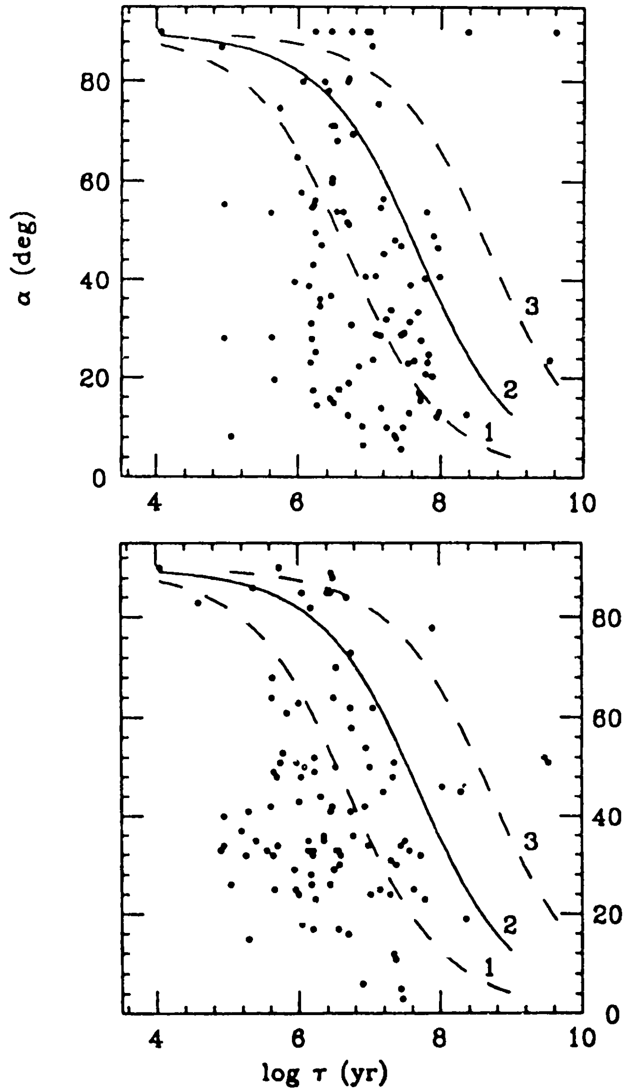

Figure 3 Obliqueness *vs.* spindown age for pulsars in the sample of Lyne and Manchester (1988) (*upper panel*) and (Rankin (1990) (*lower panel*). The curves marked 1, 2, 3 correspond to the expected upper envelope of the distribution in the aligning vacuum-dipole model, for alignment timescales of 10^7, 10^8 and 10^9 yr, respectively.

$$N = I\dot{\Omega} = \frac{2}{3c^3} B_s^2 R^6 \Omega^3 f(\alpha) \qquad (4)$$

where $f(\alpha)$ is the unknown dependence of the torque on obliqueness, which equals $\sin^2\alpha$ in the vacuum dipole model. In terms of the spin period and spindown rate, eq.(4) can be rewritten as

$$P\dot{P} = \left(\frac{8\pi^2 R^6}{3c^3 I}\right) B_s^2 f(\alpha). \qquad (5)$$

The nature of $f(\alpha)$ can therefore be revealed by plotting $P\dot{P}$ against α, as shown in figure 4 (Bhattacharya 1989). The solid line shows the trend expected according to the vacuum dipole model [*i.e.* $f(\alpha) = \sin^2\alpha$]. As can be clearly seen from figure 4, the distribution of $P\dot{P}$, and hence the spindown torque, is essentially independent of the obliqueness, which indicates that the true reason behind torque decay must be a decay of the magnetic field strength B_s. A simultaneous implication of this is that the conventional assumption of $\sin\alpha = 1$ in estimating the field strength B_s [*cf.* eq.(1)] is expected to give reliable results irrespective of obliqueness, contrary to some recent suggestions in the literature (Blair and Candy 1989).

Long-term evolution: The residual field

The above arguments for field decay come from normal radio pulsars, most of which cease to function within 10^7 yr. To probe the evolution of the magnetic field over much longer timescales, one needs to use the so-called "recycled" pulsars, spun-up due to accretion in binary systems. They are characterized by their short periods and their association with evolved binary companions. These neutron stars are at least as old as the sum of the "wait" period for the mass transfer to begin after the formation of the neutron star and the duration of the mass-transfer phase. Depending on the kind of binary system the neutron star was born in, their present ages can range from a few million years to several times 10^9 years. It is significant that most of these pulsars have magnetic fields much lower than the normal population of radio pulsars. Also, the pulsars processed in massive X-ray binaries with short evolutionary timescales have, in general, higher fields than those processed in low-mass X-ray binaries with long evolutionary timescales. The derived ages and the magnetic fields of these neutron stars appear to be consistent with an exponential decay having a time constant of ~5 million years (Taam and van den Heuvel 1986).

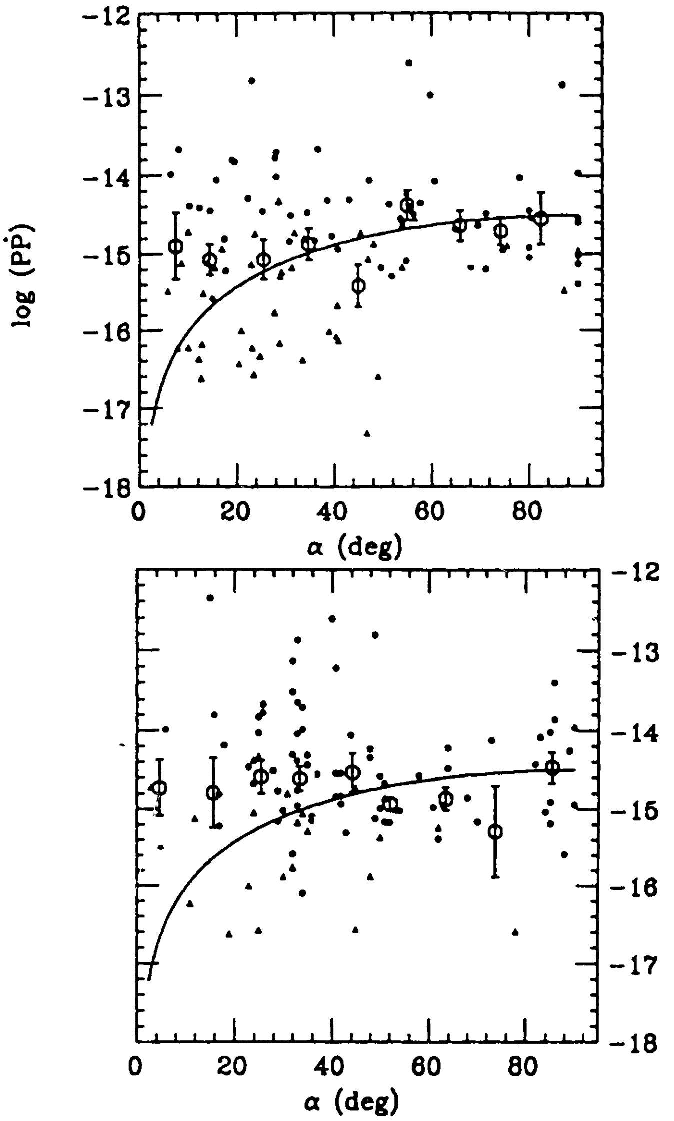

Figure 4 A measure of the spindown torque, log($P\dot{P}$), is plotted against the obliqueness for pulsars in the sample of Lyne and Manchester (1988) (*upper panel*) and Rankin (1990) (*lower panel*). Also plotted are the average values of log ($P\dot{P}$) over 10°-wide bins of α, with $\pm 1\sigma$ error bars. The filled circles represent pulsars with spindown ages $< 10^7$ yr, and the triangles those with spindown age $> 10^7$ yr.

Recent evidence suggests, however, that such a decay does not continue for ever. The argument for this comes from at least two independent quarters:

1. The white dwarf companions of at least two binary pulsars have now been detected (Kulkarni 1986). Among these, the companion white dwarf of PSR 0655+64 has a rather low surface temperature, which indicates a "cooling age" in excess of 10^9 yr. The age of the neutron star, the first born member of the binary system (see, *e.g.* van den Heuvel 1984), must be even larger than this. Nevertheless, this neutron star has retained a magnetic field $\sim 10^{10}$ Gauss. If the magnetic field continued to decay with an *e*-folding timescale of a few million years, then the expected field at present would be practically zero, and the pulsar activity would have ceased a long time ago.

2. The second piece of evidence comes from the statistics of millisecond pulsars (Bhattacharya and Srinivasan 1986, van den Heuvel, van Paradijs, and Taam 1986). The prolonged accretion required for spinning a neutron star up to a millisecond period, as well as the nature of their binary companions suggest that the progenitors of millisecond pulsars must be low-mass X-ray binaries. The small volume of the galaxy in which the millisecond pulsars have been detected, and the possible selection effects against their detection suggest that the total number of active millisecond pulsars in the galaxy exceeds that of low-mass X-ray binaries by a factor of *at least* 100 (Bhattacharya and Srinivasan 1986, Kulkarni and Narayan 1988, Coté and Pylyser 1989). This means that the active lifetimes of millisecond pulsars must be larger than that of low-mass X-ray binaries by a similar factor. Since the active lifetimes of low-mass X-ray binaries are estimated to be in the range 10^7 to 10^8 yr, that of millisecond pulsars must be larger than 10^9 yr. This would just not be possible if their magnetic fields continue to decay on a $\lesssim 10^7$ yr timescale.

These arguments indicate that the magnetic field of a neutron star, after an initial decay, reaches an asymptotic minimum value. The strength of this "residual field" could vary between neutron stars: the magnetic fields of all the known millisecond pulsars in the galactic disk have nearly the same value (within a factor of about 3), but the field of the pulsar PSR 0655+64 is about an order of magnitude above this value. The recent discovery of cyclotron lines in the X-ray spectra of γ-ray bursters (which are likely to be very old neutron stars) indicate "residual fields" $\sim 10^{12}$ Gauss in these objects (Murakami *et al.* 1988). The magnetic fields of two other accreting neutron stars, namely Her X-1 and 4U 1626−67 also appear to indicate "residual" values of order 10^{12} Gauss (Verbunt, Wijers, and Burm 1990).

Field decay due to mass accretion?

The fact that the "residual" field strengths of neutron stars may cover almost the entire range of observed fields raises the obvious question as to what determines the extent to which the magnetic field of a neutron star decays. Indeed in the conventional picture of spontaneous decay of the magnetic field due to ohmic dissipation of currents in the crust, it is very difficult to understand why the magnetic fields of different neutron stars should decay by widely different amounts. A promising explanation appears to be that the magnetic field of a neutron star decays significantly only when it accretes matter from a binary companion.

It must be noted that all observed neutron stars which possess significantly low field strengths either are, or bear distinct characteristics of having been, members of accreting binary systems. These neutron stars also exhibit a general correlation between the amount of matter accreted from the companion and the degree of magnetic field decay (Taam and van den Heuvel 1986). Further, on re-examining the relation between the kinetic ages and the spindown ages of radio pulsars (see above), Bailes (1989) came to the conclusion that those pulsars which are likely to have been "recycled", exhibit little field decay *after* the end of mass transfer. All this seems to point to the fact that mass accretion plays a central role in the decay of neutron-star magnetic fields.

What physical mechanism may cause a decay of the magnetic field of an accreting neutron star? It was suggested by Bisnovatyi-Kogan and Komberg (1974) that the accreted matter may screen and bury the magnetic field of a neutron star, and thus, even if the intrinsic field of the neutron star does not decay, the exterior dipole field may diminish.

More recently, several authors have attempted to construct models of the decay of the *intrinsic* magnetic field due to accretion. These efforts have been sparked, in part, by the difficulties in understanding spontaneous field decay by as much as four orders of magnitude (as seems to be the case in "millisecond" pulsars) from a theoretical point of view. It was shown by Sang and Chanmugam (1987) that even if the entire initial magnetic flux of the neutron star is confined to the upper crust with a low conductivity, a significant part of it eventually diffuses into the highly conducting lower crust, and the net field decay does not exceed about an order of magnitude in a Hubble time.

Mass accretion onto the neutron-star surface may, however, modify this picture significantly [see, *e.g.* (Romani and Hernquist 1992)]. The heating of the crust due to accretion will cause the crustal conductivity to drop, thus hastening ohmic decay of the currents there. Further, if the original flux is entirely confined to the crust, then the compression of the current-carrying layers due to the accreted overburden may cause a large reduction in the dipole moment by bringing opposing current loops into close contact (Romani 1990b). An inverse thermoelectric battery effect may also operate and destroy the crustal flux, aided by thermally-induced field convection transporting flux outwards from deeper layers (Blondin and Freese 1986). Such mechanisms of field destruction would predict a direct relation between the amount of matter accreted and the amount of flux destroyed. A simple form of such a relation, examined by Shibazaki *et al.* (1989), seems to reproduce the observed field-period combinations of the recycled pulsars quite well. However, one counter-example has recently been pointed out: the neutron star in the X-ray binary 4U 1626−67 has accreted a large quantity of mass, but has still retained a magnetic field $\sim 10^{12}$ Gauss (Verbunt, Wijers, and Burm 1990).

The mechanisms just discussed are relevant only if the original magnetic field is confined entirely to the crust. If the magnetic flux is entrained in the superconducting interior, none of these effects can influence the magnetic field. A completely different mechanism may, however, operate to relate the evolution of the "core" magnetic field to the accretion process (Srinivasan *et al.* 1990).

Field decay due to spindown

The interior of a neutron star is believed to be composed of superfluid neutrons and superconducting protons. The spin angular momentum of the neutron star is carried by quantized Onsager-Feynman vortex lines in the superfluid neutron component, and any magnetic flux passing through the interior is confined to quantized Abrikosov fluxoids in the superconducting proton component (see Sauls 1989 for an excellent review). If the magnetic field of the neutron star has to decay, these fluxoids must be expelled from the superconducting region. Muslimov and Tsygan (1985) pointed out that such an expulsion may indeed occur due to the buoyancy force acting on the fluxoids. The timescale for fluxoid expulsion has been somewhat controversial, but most authors now agree that if the buoyancy force and a drag due to electron scattering are the only forces acting on a fluxoid, the flux can be expelled from the interior in $\lesssim 10^7$ yr (see *e.g.* Jones 1987, 1988).

An additional effect, however, is most likely to frustrate such a flux expulsion. As has been recently pointed out (Sauls 1989, Srinivasan *et al.* 1990), a strong tendency of pinning may exist between the proton flux tubes and the neutron vortex lines, which would make it impossible for these entities to move independently of each other. Sauls (1989, 1990) estimates that the elementary pinning energy between a fluxoid and a vortex line is ~0.1–1 MeV per connection, which translates into a pinning force of $\sim 10^5$–10^6 dyne/connection. The electromagnetic interaction between a fluxoid and a vortex line also gives rise to a force of a similar magnitude. Since a fluxoid experiences a buoyancy force $\sim 10^7$ dyne over its entire length, it only needs to be pinned at 10 to 100 points to prevent it from floating up. A simple estimate, taking into account the repulsion between the fluxoids, their mean separation, and the pinning force, suggests that $(5-50)\times 10^{15}$ pinning centers would be available on *each* neutron vortex line. Since the total number of vortex lines in the superfluid amounts to $\simeq 2\times 10^{16} P^{-1}$, where P is the spin period of the neutron star in seconds, the effective number of fluxoids "trapped" against floating would be $\sim(10^{30}-10^{32})P^{-1}$, equivalent to a "trapped" magnetic field $\sim(10^{11}\text{-}10^{13})P^{-1}$ Gauss. Thus most of the fossil field may be trapped in the interior owing to the entanglement of the flux lines with the neutron vortices (Srinivasan *et al.* 1990).

When a neutron star spins down, the number of neutron vortices in the superfluid decreases by moving outwards and annihilating at the superfluid boundary. These moving vortex lines will also carry the pinned fluxoids with them, causing an expulsion of the flux from the interior (even if the vortices are unable to actually carry all the pinned flux along, they will at least leave the fluxoids to float up freely). The amount of flux retained in the interior will thus be determined directly by the spin period of the neutron star. The spin evolution of an isolated neutron star due to dipole braking [*cf.* eq.3] with $B_s \propto \Omega$ would result in a very slow field evolution $B_s \propto t^{-1/4}$, with a net decay of only about an order of magnitude in a Hubble time (Srinivasan *et al.* 1990).

Neutron stars in binaries can, however, be spun down to much longer periods, especially during phases of weak accretion from the companion's stellar wind. Spin periods as long as 835 s have been observed among the binary X-ray pulsars. Such a spindown will reduce the number of vortex lines, and consequently the number of fluxoids, by a large factor, causing a substantial field decay. Subsequently, strong accretion will spin the neutron star up to a short period (leaving a "recycled pulsar" in the end); but this process will inject new vortices into the core, and all the remaining flux will be trapped there forever. Thus, according to this model, the "residual" field of a neutron star will be determined by the *maximum* spin period to which the star is spun down in its binary history (Srinivasan *et al.* 1990).

Source of the "normal" pulsar population

The intimate connection between the evolution of a neutron star in a binary system and the behavior of its magnetic field thus appears to provide a very promising explanation for the long-term behavior of the magnetic field. Is it possible to understand the signs of field decay exhibited by the population of *solitary* pulsars based on such a hypothesis? The answer is yes, provided a significant fraction (~50%) of the solitary pulsar population is composed of *recycled* pulsars processed in binaries. This immediately raises the question as to whether there are enough progenitor binaries that can provide such a large number of isolated recycled pulsars.

The objects that are likely to produce a significantly large number of recycled pulsars—and also cause the disruption of the binary in a second supernova explosion—are neutron-star binaries with B/Be star companions. Some of these binaries are visible as transient X-ray sources. Observations by the Ginga satellite indicate that there is a large population of such objects in the galaxy (Koyama 1988). Meurs and van den Heuvel (1989) have recently estimated this number to be at least $\sim 2\times 10^4$. Since these binaries have a typical lifetime of $\sim 10^7$ yr, they can provide $\gtrsim 10\%$ of the pulsar birthrate in *recycled* pulsars alone. Further, since the active lifetime of a radio pulsar in the absence of field decay is inversely proportional to its field strength, these recycled pulsars—despite their lower birthrate—can constitute a huge fraction of the total pulsar population if the processing of these neutron stars in binaries decreases their field strengths by, say, an order of magnitude.

I close this discussion with a word of caution regarding the use of the z-distances of pulsars as a possible measure of their ages. As we have seen, the absence of pulsars beyond a z of ~1 kpc has been widely interpreted as an indication of the average pulsar lifetime being $\lesssim 10^7$ yr. If field decay is related to binary evolution, then, as mentioned above, one expects a fraction of radio pulsars to have lifetimes much longer than this. With a z-velocity of $\sim 100\,\mathrm{km\,s^{-1}}$ such a pulsar would move several kiloparsecs away from the galactic plane, which is not observed. However, most of the distances to radio pulsars are obtained from their dispersion measures, *i.e.* the column density of thermal electrons in the line of sight. Recent observations of radio pulsars in globular clusters clearly show that this electron layer has a scale height of ~500-1000 pc (Reynolds 1989, Bhattacharya and Verbunt 1990). This would lead to an underestimate of the distances of radio pulsars far away from the galactic plane. Pulsars currently thought to be located at $\lesssim 1$ kpc may in fact be at higher z. Thus the observed z-distribution of radio pulsars cannot be taken as a contradiction to a longer-than-10^7 yr lifetime for some pulsars (Bhattacharya and Verbunt 1990).

Conclusions

The main conclusions we can arrive at from the above discussions are the following:

1. The decay of the spindown torque on radio pulsars occurs due to a real decrease of the field strength and not due to an evolution of "obliqueness".

2. There are strong observational indications that the decay of the magnetic field is closely related to the processing of the neutron star in a binary system. If the flux is originally confined to the crust, this may happen due to the modifications of the crustal properties due to accretion. If the flux is confined to the superconducting interior, the field decay will be closely related to the spindown of the neutron star. The "residual" field strengths will in these two cases be determined by the total amount of matter accreted, and the maximum spindown of the neutron star, respectively.

3. The most likely explanation of the signs of field decay exhibited by the population of solitary pulsars is that it contains a large sub-population of recycled pulsars, coming from B/Be star + neutron star binaries.