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Spin-Driven Changes in Neutron Star Magnetic Fields

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Abstract. Interactions among a neutron star's superfluid neutrons, superconducting protons, and solid crust cause predictable spin-down and spin-up driven crustal motion and magnetic field changes. Applications and unsolved problems are discussed for millisecond pulsar evolution and properties, glitches and post-glitch responses, and transient gamma-ray emission.

1. Crust Motion and Magnetic Field Evolution

Several years ago Sauls (1989) and Srinivasan *et al.* (1990) noted that nuclear interactions between neutron superfluid vortex lines and proton superconductor magnetic flux tubes within a neutron star's core could give a coupling between the star's magnetic field and its spin (Ω). This argument was later strengthened by including the effect of a neutron vortex line's own strong magnetic field (Ruderman 1991a,b). The core flux is no longer quantized into flux tubes as it passes out of the star through the crust. (Crustal nuclei are themselves superconductors but because their radii are less than their magnetic penetration depth (London length) they are not very effective in channeling \mathbf{B} through the crustal lattice.) The almost rigid strongly conducting stellar crust does not permit the exterior surface field to adjust to the core flux motion beneath it unless either the crust's yield strength is exceeded or the time scale for changes is so long that finite crust conductivity allows diffusion. The latter is probably unimportant in young (age $\lesssim 10^6$ years) neutron stars and perhaps in all. If we ignore it, the stress on the crust from the core's moving flux tubes (whose ends are anchored in the crust base) would continue to grow as the core vortex line-flux tube complex moves out (in) during spin-down (spin-up). Then either the crust stress will ultimately exceed the yield strength, or the core's vortex lines will be forced to cut through the core's flux tubes. Estimates of the crust's yield strength indicate that the former should preempt the latter: the crust breaks to allow those regions which carry most of the flux through it (polar caps) to follow the core flux tube motions below them. More weakly magnetized or unmagnetized crust regions would be forced to move in an opposite direction to give a compensating crustal backflow

if stratification suppresses crustal radial flow. Crustal stresses from the crust's own pinned neutron superfluid vortex lines (Alpar *et al.* 1984; Ruderman 1976; Anderson and Itoh 1975) can add to those from core flux tube pull to move crustal "plates" (Ruderman 1991a,b,c).

The surface fields of a spinning-up neutron star should then evolve as indicated in Figs. 1, 2 and 3. Corresponding changes in the neutron star's dipole moment are shown in Fig. 4. Comparisons between the descriptions of Figs. 1–4 and observations support the indicated evolution and the following details:

(a) In the early spinning-down segment $\overline{01}$ for a young radio pulsar, the dipole B of Fig. 2 can grow (Ruderman 1991b) so that the spin-down index $n(\dot{\Omega} \propto -\Omega^n)$ satisfies $2 \lesssim n \lesssim 3$. This indeed is the case for the young pulsars PSR 1509 ($n = 2.8$), PSR 0540 ($n = 2$), and the Crab ($n = 2.5$). The values of n should increase for older pulsars but not above about 5.

(b) In all cases of accretion induced spinup, $\overline{37}$, $\overline{46}$, $\overline{345}$, the polar caps get pushed to the spin axis. Consequently the small accretion heated polar caps, if visible, would not have their thermal X-ray emission eclipsed as the star spins. This is consistent with the failure of Ginga to observe spin modulation of X-rays in LMXB's (believed to contain strongly spun-up neutron stars).

(c) The "sunspot" configuration of Fig. 2 allows maximum spin-up since the magnetic dipole continues to decrease (as $\Omega^{-1/2}$) until the accretion spin-up line is reached. For near Eddington limit accretion, the spin-up P and dipole B are then just those of the fastest millisecond pulsars, e.g., PSR 1937.

(d) The remarkable radioemission properties of the fastest pulsars, PSR 1937, shown in Fig. 5 and PSR 1957, are precisely those expected from the limiting field configuration of Fig. 6 (Chen and Ruderman 1993). A crucial feature is gravitational bending of "core" emission beams through closed field line parts of the magnetosphere and the effect of the magnetosphere on the radio beams which pass through it.

(e) Accretion induced spin-up of neutron stars with Fig. 1, or with Fig. 3 type field geometry with small S_1 (evolution paths between $3 \rightarrow 7$ and the reversal $3 \rightarrow 2$ in Fig. 4), will lead to canonical large dipole moment pulsars with periods $P \sim 0.1 - 1$ s. That there is an even larger population of such spun-up stars than of millisecond pulsars is suggested by analysis of the genesis of the binaries PSR 1831–00 and PSR 1718–19 (van den Heuvel, these Proceedings).

All of the above comparisons with observations, especially (d), support confidence that the spin-up induced crust motion and magnetic field evolution of Figs. 1–4 are a generally correct description. Then it should be possible to use the model's predictions as a tool to discriminate between millisecond pulsars which have been spun-up and those which may have been born as millisecond pulsars. There seems to be no apparent reason for the magnetic field geometry of the latter to resemble any of the limiting ones of Figs. 1–3.

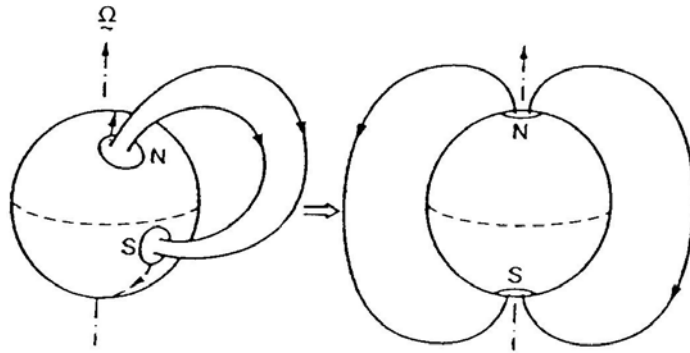


Figure 1: Evolution of the surface magnetic field of a spinning-up short-period neutron star when flux lines initially connect the two spin hemispheres.

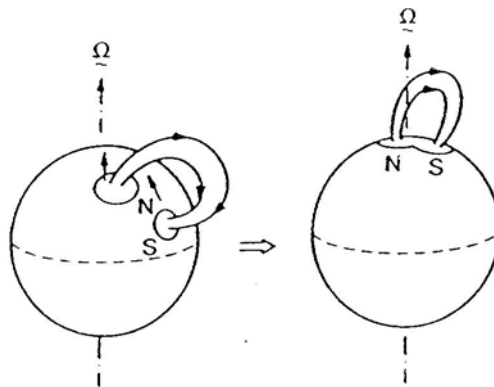


Figure 2: Evolution of the magnetic field of a spinning-up short-period neutron star when all flux leaving a hemisphere reenters the same hemisphere ("sunspot" configuration).

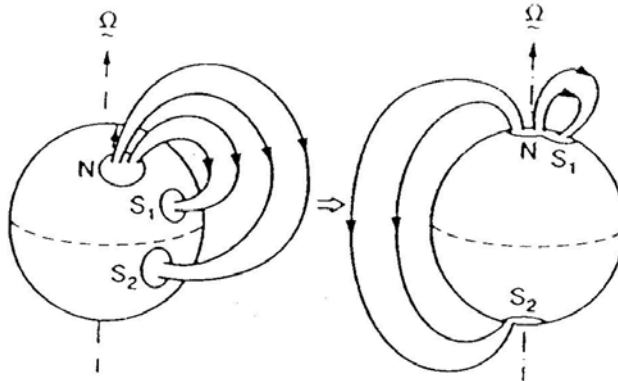


Figure 3: Evolution of the magnetic field of a spinning-up short-period neutron star with an initial flux configuration which is intermediate between that of Figs. 1 and 2.

2. Modelling the Radioemission Beam Geometry of Spun-Up Millisecond Pulsars

The fastest pulsar, PSR 1937, appears to be especially simple for two reasons: (a) its spun-up field geometry seems well described by Fig. 6; (b) the observed emission seems to have only “core components” whose source is close to the stellar surface (Rankin 1990). The absent “conal components” would have to be emitted from much further from the stellar surface, where they would not be gravitationally bent into a fan beam (Chen and Ruderman 1993) and thus might be more easily missed than the fan-beamed core component. A conal component would, however, be seen by an observer nearly perpendicular to the spin axis. Such a geometry is implied for PSR 1957 ($P = 1.6$ ms) by the observed eclipse by its secondary and for it a conal component is indeed also present (Fig. 7). For stronger field, longer period millisecond pulsars we expect the additional complication that these pulsars have been less spun-up because their field configurations resemble that of Fig. 3. The magnetic flux between N and S_2 gives a dipole moment component that cannot be diminished by further spin-up; this is why such a star reaches the accretion limit spin-up line with larger B and, thus, longer P than PSR 1937. The expected radioemission pulse geometry from a Fig. 3 configuration can be explored analytically for a two-dimensional model. When the dipole moment component parallel to $\Omega(d_{\parallel})$ is less than $2/\pi$ times d_{\perp} (the perpendicular component), the two open field line bundles (which determine the radiation beaming) attach to the star as indicated in Fig. 8a. The field geometry is similar to that of Fig. 6, and two gravitationally bent core-emission fan beams can be formed as in that case.

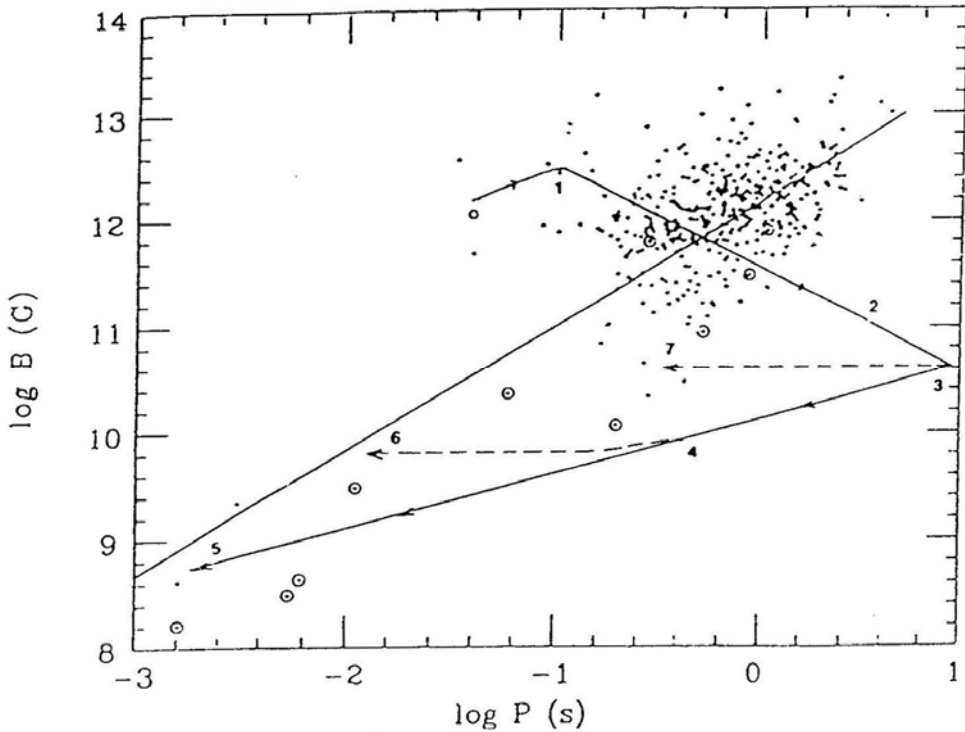


Figure 4: Evolution of dipole magnetic fields. Solitary radio pulsar spin-down would reach 2. Segment 12: $B \propto \Omega$ as crust plates move toward the equator where pole reconnection takes place. Some further spin-down to 3 is assumed if in an accreting binary. Spin-down below 3 would not be effective in reducing B , because the crust would no longer be stressed above its yield strength. Subsequent accretion induced spin-up would return the neutron star to 3, after which its evolution depends upon the magnetic field configuration. Segment $\overline{345}$ (solid line) is that for a sunspot-like configuration of Fig. 2. Segment $\overline{37}$ (dashed line) is that for a configuration of Fig. 1. Fig. 3 would give $\overline{346}$, intermediate between these two. The dots are for solitary radiopulsars; the circled dots are radiopulsars in binaries.

However, when $d_{\parallel} \geq 2d_{\perp}/\pi$ the South pole open field line bundle jumps from S_1 to S_2 as in Fig. 8b. Gravitational bending of any core component emission would, if it exists, now give two fan beams with opposite polar angle spread. No one observer would any longer be likely to see two 180° separated core components with anything like comparable intensities. This qualitative conclusion seems robust enough to be valid in a three-dimensional model, but much needs to be explored quantitatively in three dimensions about the expected radioemission properties for field geometries like those of Fig. 3 which give less than the maximum millisecond pulsar spin-up.

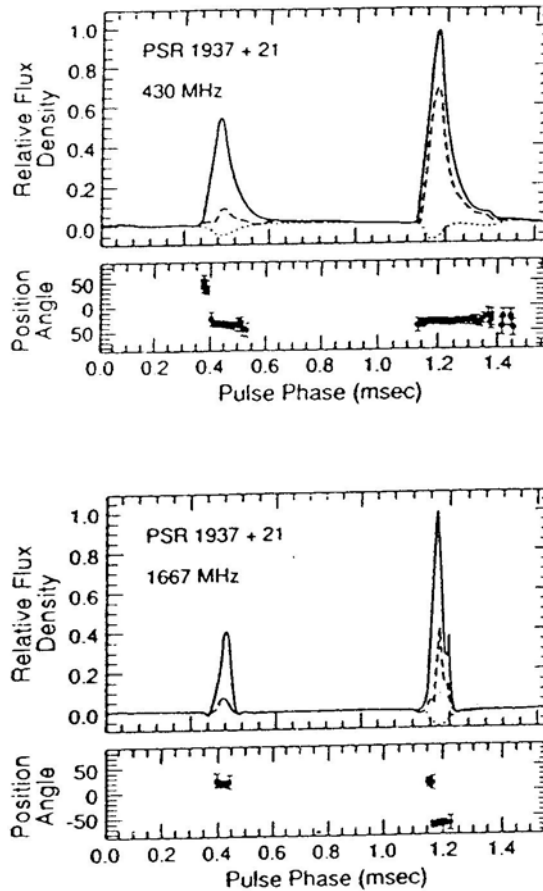


Figure 5: Pulse shape and polarization for PSR 1937+214 at 430 and 1667 MHz, respectively. The dashed line is the linearly polarized intensity; its position angle is shown below (Thorsett 1990).

3. Distinguishing Spun-Up Millisecond Pulsars from Pulsars Born with High Spin

As discussed above this now seems possible if the spin-period $P \sim 1.6$ ms as in PSRs 1937 and 1957, but not yet for significantly larger P . However, strongly spun-up pulsars would always have very small angular spread of open field lines at one of the poles (N in Figs. 8a, 8b) on the stellar surface, and further consequences of this should be explored. With a greater sample of pulsars with $P \lesssim 3$ ms (?) it may even now be possible to test whether globular cluster millisecond pulsars are spun-up by accretion (as seems confirmed for the disc population PSR 1937) or are born spinning rapidly (e.g., accretion induced collapse of White Dwarfs, fusion

of orbiting collapsed stars, capture of collapsed stars by Red Giant cores, etc.). Improved pulse shape resolution for globular cluster millisecond pulsars will be important. A first analysis for 47 Tuc, based upon poorly resolved data, suggested that the fastest of those globular cluster millisecond pulsars may indeed have been born with their fast spins (Chen and Ruderman 1993) but better time resolution is needed.

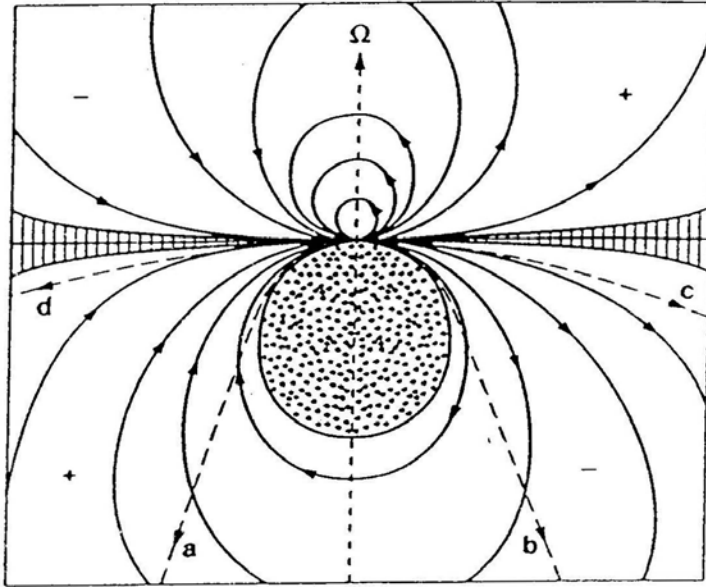


Figure 6: Magnetosphere of a strongly spun-up diamagnetic (because of core proton superconductivity) neutron star with the initial field geometry of Fig. 2 (from Chen and Ruderman 1993). One fan beam (cb) passes through electron filled magnetosphere, the other (da) through ions.

4. Magnetic Flux Tube Motion and Post-Glitch Responses in Neutron Star Cores

Much important microphysics on how vortex lines move flux tubes, under what circumstances they cut through them, moving flux tubes' drag, and just how the crust yields to flux tube stress, remain to be explored more quantitatively. Especially important is the flow of the core's electron plus superconducting-proton plasma through a moving flux tube array. This would be almost impossible if the protons were not superconducting. In that event the electron-proton plasma would move as if attached to the flux tubes just as a more conventional magnetic field distribution is frozen into an almost perfectly conducting classical fluid. However,

within the superconductor, the total ($e + p$) current density (\mathbf{j}) satisfies

$$4\pi\mathbf{j} = \Lambda^2\nabla^2\mathbf{j}_p,$$

where \mathbf{j}_p is the proton superconductor's current and Λ is its London penetration length ($c/\text{plasma frequency}$). The screening current seems to allow flux tubes to move independently through $e - p$ fluid (and possibly to bunch when pushed by neutron vortex lines). This is essential in understanding why the core's flux tubes move with its moving vortex lines rather than remaining immobile and being cut through by them. K.S. Cheng and M.R. have found that even the drag on a single moving flux tube is greatly reduced from previous estimates by this diamagnetic screening.

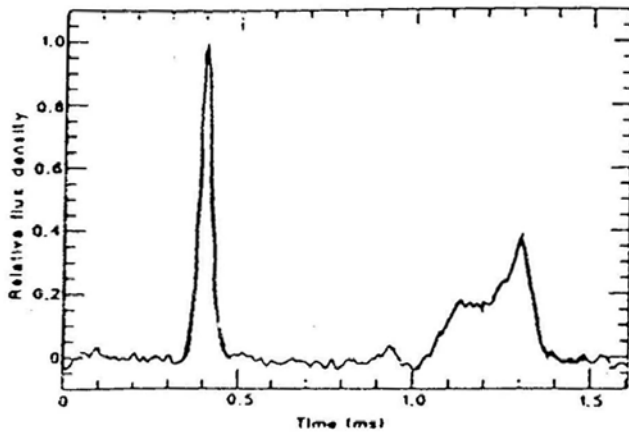


Figure 7: A pulse profile of PSR 1957+20.

Another important consequence of the flux tube – vortex line coupling is to the glitch and post-glitch response of a pulsar's core neutrons. Present models presume that all of a core's superfluid neutrons extremely rapidly adjust their rotation velocity to a suddenly changed one of core electrons and protons ($\lesssim 10^2$ s) (Alpar *et al.* 1984; Alpar *et al.* 1993). However, the neutron vortex – proton flux tube interaction could greatly affect this and it must be examined more closely and quantitatively. Preliminary theoretical estimates and observations both suggest a resulting “sluggishness” in neutron vortex response is observable in Crab glitches.

5. Crust Movement and Glitches

It has been argued (Ruderman 1991c; Ruderman 1976) that if spin-down induced crustal stresses are relieved by large scale crust cracking the resulting sudden jumps in pulsar spin-rate have a magnitude and repetition rate similar to those of the large glitches observed in the Vela family of radio pulsars (PSRs 0833, 1737, 1800, 1758, and 1823). Large crust cracking should also give a permanent change in magnetic dipole and thus part (of order 10^{-4}) of a glitch associated

$\Lambda \dot{\Omega} / \dot{\Omega}$ should not “heal”. In addition to large glitches in the Vela-like family and some older pulsars there are very much smaller ones in the Crab pulsar, numerous microglitches in Vela, and timing “noise” quite generally. The glitch variety may, in part at least, be related to the complications of breaking phenomena in the highly structured neutron star crust. For example, the various crustal layers have lattices composed of different nuclei which may change rather discontinuously at layer boundaries. This would give rise to jumps there in lattice properties (and vortex pinning strengths) which complicate the description of how and where a lattice cracks. If slippage along layer boundaries is easier than other crustal breaks a variety of glitch responses may exist because sudden cracking can occur separately in layers with very different properties (e.g., the moment of inertia of the superfluid they contain). Crust cracking complexities, as well as temperature differences, may contribute to the variety of observed glitch-like changes in pulsar periods and period derivatives.

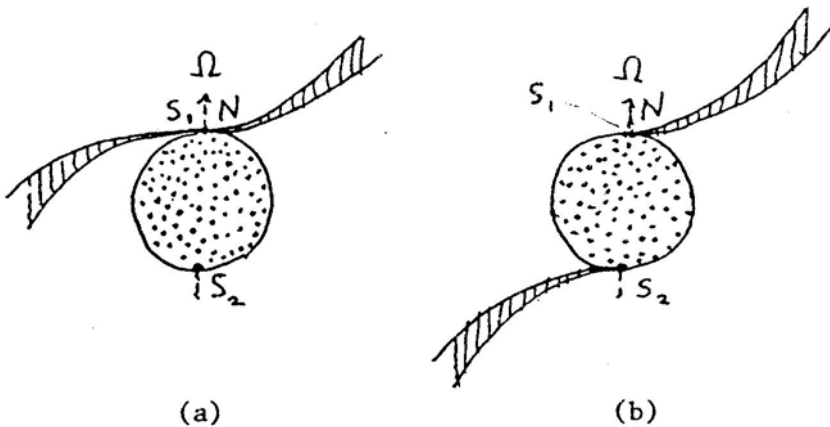


Figure 8: Open field line bundles for two-dimensional stars with Fig. 3 geometries. a) $d_{\perp} > (\pi/2)d_{\parallel}$, b) $d_{\perp} < (\pi/2)d_{\parallel}$.

6. Gamma-Ray Transients (Soft Gamma-Ray Repeaters)

One consequence of neutron vortex line – proton flux tube coupling is that extraordinarily large crust-cracking events (followed by a series of smaller ones) would be expected in a spinning-down neutron star whenever spin-down expels enough flux from the stellar core into the equatorial regions of the lower crust. Although this sort of event should occur less than once a millenium for a Vela-like pulsar, it should happen every few decades in a 10^4 year old pulsar with a magnetic field of several times 10^{14} G. Such a strongly magnetized pulsar, although still in an observable supernova remnant, would have spun-down to a 2 – 10 s period. The

possibility that Soft Gamma-Ray Repeaters are very strongly magnetized neutron stars has already been proposed by Duncan and Thompson (1992, 1993) and is being explored further by M.R. and M. Tavani. The energy release in the initial huge cracking event, powered by the sudden field reconnection, depends upon the yield strength of the crust. That from the “after-shocks” is of order the amount of elastic energy which can be stored in crustal strain and suddenly released. Theoretical estimates of both (10^{45} ergs and 10^{41} ergs respectively) give values very suggestive of those of the well known “March 5” gamma-ray burst and its series of after-bursts. The periodic modulation of its burst X-rays strongly supports an origin in a neutron star with an 8 sec. spin period. The apparent burst location in an LMC supernova remnant implies a burst energy above 10^{44} ergs, almost as great as the *total* spin energy of the star. However, the magnetic field energy within the stellar core (bunched into hugely magnetized quantized flux tubes) is about $B_{14}10^{47}$ ergs, enough for a neutron star with an external dipole field of $B \sim 3 \cdot 10^{14}$ G to power several thousand such bursts and nearly a million of the much weaker “after-bursts”. Thus the needed energy is available in such a star’s magnetic field if there is a mechanism to push the field out of the star’s superconducting core. Spin-down induced flux tube motion by moving neutron vortex lines may supply it.

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