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Evolution of the Magnetic Fields of Neutron Stars in Low-mass Binary Systems

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Abstract. We investigate the evolution of magnetic fields of neutron stars in 'wide' low-mass binary systems due to the spin-down of the neutron star, resulting from an interaction with the stellar wind of the companion. We assume that magnetic flux from the neutron star core is expelled to the crust as the neutron star spins down due to the proposed vortex-fluxoid pinning interaction in the superfluid interior (Srinivasan *et al.* 1990). Once deposited in the crust the field will then decay due to ohmic dissipation. We construct models with a range of donor masses, orbital periods, mass-loss rates, and assumed ohmic decay timescales in the crust, and compute the final magnetic field strengths of the neutron stars. We find that the magnetic fields of millisecond pulsars, as well as other low-mass binary pulsars may be well accounted for by this mechanism if the ohmic decay timescale at the bottom of a neutron star crust is $\sim 10^9$ years. The models seem to further indicate that an asymptotic value $\sim 10^8$ G is the lowest possible field strength obtainable by this mechanism.

Key words: Neutron stars—pulsars—magnetic fields—binary systems.

1. Introduction

The low magnetic field strengths ($\geqslant 10^8$ G) of millisecond pulsars could be due either to their progenitor neutron stars being born with such low fields or to a decay of their field strengths in course of evolution. Recent analyses of observational data suggest that magnetic fields of isolated neutron stars hardly decay in time scales $\leqslant 10^8$ yr (Bhattacharya & Srinivasan 1993; Srinivasan 1991; Wakatsuki *et al.* 1992). The large preponderance of low-field pulsars in binary systems, however, indicates that the processing in a binary causes a reduction of the field strength of a neutron star (Bailes 1989; Bhattacharya *et al.* 1992).

One suggested mechanism for such a field evolution is a spin-down induced field expulsion (Srinivasan *et al.* 1990), which advocates the following scenario:

- An increase in the spin period causes the magnetic field to be expelled out of the core into the crust, where it will decay due to ohmic dissipation. The expulsion is expected as a result of the interpinning of proton superconductor fluxoids (carrying magnetic field) and neutron superfluid vortices (carrying angular momentum) in the neutron star core. With spin-down, superfluid vortices migrate outward, carrying fluxoids with them.

- In the evolution of low-mass binaries a prolonged spin-down ('propeller') phase is likely to take place, resulting in a period $> 10^3$ sec, and a consequent reduction in the core flux.

2. The present work and results

In this work we model the evolution spin periods and magnetic fields of the neutron stars in wide low-mass binaries, which are believed to be the progenitors of low-magnetic-field pulsars. We adopt the above field-decay mechanism and seek the conditions under which an efficient spin-down phase (due to interaction with the stellar wind of the donor) might be realised, resulting in a low magnetic field of the descendant millisecond pulsar. We construct our evolutionary models based on the following premises:

- Wind matter can penetrate into the star's magnetosphere if ram pressure of the accretion flow ($\dot{M}_{\rm acc}$) exceeds the pressure of dipole radiation.
- At the Alfvén radius $R_{\rm A}$, interaction of the flow and the magnetic field causes the spin period P to increase or decrease depending on the relative value of the two velocities $V_{\rm corotation}$ and $V_{\rm keplerian}$ at $R_{\rm A}$:

$$\dot{P} \propto \xi (V_{\rm corotation} - V_{\rm keplerian})$$

where $\dot{P}$ is the rate of change of P and ξ is an efficiency factor.

- The core field $B_{\rm c}$ decreases with an increase in P.
- The surface field $B_{\rm s}$ approaches $B_{\rm c}$ exponentially with a time constant τ, and they are equal at the start.
- Instantaneous $B_{\rm s}$ and $\dot{M}_{\rm acc}$ determine the instantaneous $R_{\rm A}$.
- Changes in orbital separation occur due to exchange and losses of angular momentum and mass.

We follow the coupled evolution of P and $B_{\rm s}$ and determine $B_{\rm s}$ after 10^{10} yr, for the following ranges of variables: Donor Mass M_2: $0.8 - 1.0\ M_\odot$; Initial P: $0.4 - 1.0$ sec; Initial $B_{\rm s} = B_{\rm c}$: $10^{12} - 3 \times 10^{12}$ G; τ: $10^7 - 10^{10}$ yr; ξ: $0.01 - 1.0$; Initial $P_{\rm orb}$: $1 - 300$ day. We confine ourselves to 'wide' binaries, with initial orbital periods greater than ~ 1 day, to ensure that the entire main-sequence lifetime of the secondary is spent in a detached phase.

The results of these computations, namely the final $B_{\rm s}$ values are plotted (Fig. 1) against the initial orbital periods $P_{\rm orb}$, for one set of τ, $\dot{M}$, and ξ. Circles represent the data for six observed binary pulsars (0820 + 02, 1620 − 26, 1953 + 29, 1855 + 09, J1713 + 0747, and J2019 + 2425), descended from wide low-mass X-ray binaries.

3. Conclusions

1. Magnetic fields of $10^8 - 10^9$ G, similar to millisecond pulsars, can be obtained under variety of circumstances, provided $10^{9.5} > \tau > 10^{8.5}$ yr.
2. $B_{\rm s} \sim 10^8$ G is a lower limit for the field strength of a recycled pulsar, and its value is decided by the lowest possible initial field strength and spin period of a new born neutron star.

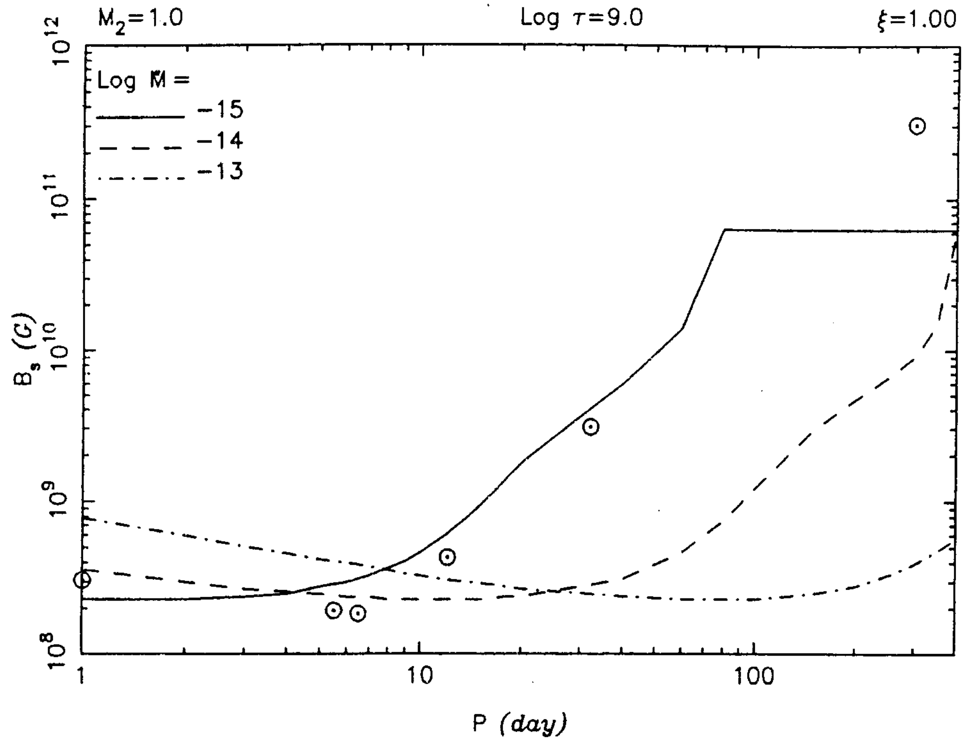

Figure 1. Final surface magnetic field strengths of neutron stars in low-mass binary systems with different orbital periods. Intial spin $P = 0.4$ sec, initial surface and core $B = 1.00\ E + 12$ G.

3. Reproduction of the observed trend of final field strengths as a function of initial orbital periods is encouraging, especially in view of the wide range of possible initial conditions.
4. Old solitary neutron stars are expected to have $B_s \sim 10^{11}$ G.
5. Extension of the work to the case of very tight orbits ($P_{\mathrm{orb}} < 0.5$ day), as well as the binaries with high-mass donor stars would provide further constraints on the scenario.

References

Bailes, M. 1989, *Astrophys. J.*, **342**, 917.

Bhattacharya, D., Srinivasan, G. 1993, in *X-ray Binaries* Eds. W. H. G. Lewin, J. van Paradijs & E. P. J., van den Heuvel (Cambridge University Press) in press.

Bhattacharya, D., Wijers, R. A. M. J., Hartman, J. W., Verbunt, F. 1992, *Astr. Astrophys.*, **254**, 198.

Srinivasan, G., Bhattacharya, D., Muslimov, A. G., Tsygan, A. I. 1990, *Curr. Sci.*, **59**, 31.

Srinivasan, G. 1991, *Ann. N Y. Acad. Sci.*, **647**, 538

Wakatsuki, S., Hikita, A., Sato, N., Itoh, N. 1992, *Astrophys. J.*, **392**, 628.