ACCRETION-INDUCED MAGNETIC FIELD DECAY AND POLARIZED PROTONS IN THE NEUTRON STAR CORE*

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We consider polarized protons in the core of a neutron star as the source of the magnetic field. The effective proton magnetic moment is density-dependent and changes sign at some density n_r and so does the magnetization. Neutron stars with the central density close to n_r have dipole magnetic field of the order of 10^{12} G. For heavier stars the field decreases fast with the mass, goes through zero and then again increases, albeit in the opposite direction. The abrupt change of the magnetic field occurs on a mass scale of 0.1 solar mass. This model accounts for recent evidence that decay of magnetic field occurs only for neutron stars which accreted matter in their evolution. Conditions are discussed for the polarized proton phase to form the ground state.

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The origin and evolution of the pulsar magnetic field remain two important unsolved problems of the neutron star physics. Recently, however, a new coherent picture of the evolution of the field is emerging [1, 2]. The evidence is accumulating that the widely accepted view that the pulsar magnetic field decays on a time scale of 10^7 years may be incorrect. Only neutron stars that have been recycled in binaries show clear evidence for

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magnetic field decay [1]. To this category belong both millisecond pulsars and binary radio pulsars, which have $B_P < 10^{10.6}$ G. These recycled pulsars probably highly contaminate the general population of single pulsars giving an impression that the magnetic fields of isolated neutron stars decay on such a relatively short time scale [3]. The recent observation of cyclotron lines from γ-ray-burst sources which are old neutron stars indicates that their magnetic fields have not decayed [4, 5].

The analysis, summarized in Ref. [1], has important implications for models of the neutron star magnetic field. It strongly indicates that the magnetic field of an isolated neutron star has the value $B_P \sim 10^{12} - 10^{13}$ G and is permanent. On the other hand, the magnetic field of recycled neutron stars is diminished with respect to these values by an amount, which is directly related to the total amount of accretion that took place during the X-ray binary phase [6], *i.e.* the decay of the magnetic field is monotonically related to the mass increase of the accreting neutron star. We show, that these features are quite naturally accounted for in a polarized proton core model which we describe below. In this model the dipole magnetic field of a neutron star is produced by a permanently magnetized matter in the dense core of the star. The magnetization results from the ferromagnetic ordered proton spins with density-dependent magnetic moments.

The neutron star core is composed mostly of neutrons with some admixture of protons, electrons and muons which form a uniform liquid of densities exceeding the nuclear saturation density $n_0 = 0.17$ fm^{-3}. The proton component is required for the beta stability of the system. The proton fraction $x = n_P/n$ is expected to be of the order of a few percent. At the saturation density n_0 the proton fraction is $x \approx 0.05$ [7], and it changes with increasing density. Various model interactions give different $x(n)$ [7], however for many realistic interactions the proton component disappears at sufficiently high densities [7]. In the calculations presented here we use the Ravenhall's parameterization of the Friedman–Pandharipande equation of state (FPR) as given by Lattimer [8]. The proton fraction for the FPR equation of state decreases from $x \approx 0.05$ at $n = 0.2$ fm^{-3} to zero at $n = 0.9$ fm^{-3} (the curve UV14+TNI in Fig. 11 in Ref. [7]). The maximum mass of the neutron star for the FPR equation of state is close to $1.8\,M_\odot$.

The proton impurities strongly influence the magnetic properties of the neutron star matter. Under certain conditions they are likely to spontaneously polarize [9]. To see this let us compare energy of polarized and normal phase assuming the proton admixture in the core to be of the order of a few percent. If the proton-neutron spin interaction is approximated by the effective contact potential with a strength g^{PN}, we can write the change of the energy per unit volume with respect to the unpolarized phase as follows:

$$\delta\epsilon = \delta\epsilon_{\rm N} + g^{\rm PN}\delta s_{\rm N}\delta s_{\rm P} + \delta\epsilon_{\rm P}\,, \qquad (1)$$

where $\delta s_{\rm N}$ and $\delta s_{\rm P}$ is the neutron and proton spin excess, respectively. The first and the third term describe, respectively, the change of the neutron and proton energies due to a small polarization. The second term represents the proton-neutron spin interaction. The main contributions to this interaction come from the one-pion exchange, the ρ-exchange and the second-order tensor interaction. These contributions, calculated in Ref. [10], give $g^{\rm PN} \approx -2$ fm^2. The change of the neutron energy density $\delta\epsilon_{\rm N}$ can be expressed in terms of the Landau Fermi-liquid theory as

$$\delta\epsilon_{\rm N} = \frac{1}{2N_{\rm N}}\left(1 + G_0^{\rm NN}\right)\delta s_{\rm N}^2\,. \qquad (2)$$

Here $N_{\rm N} = m_* k_F/\pi^2$ is the density of states at the Fermi level and $G_0^{\rm NN}$ is the spin dependent Landau parameter for pure neutron matter. Calculations of Ref. [11] show that $G_0^{\rm NN}$ depends weakly on density and we take $G_0^{\rm NN} \approx 1$ in the whole density range of interest. This shows, that pure neutron matter does not possess a ferromagnetic phase. (The ferromagnetic phase of pure neutron matter as the source of the magnetic field of neutron stars was considered in Ref. [12], however, subsequent sophisticated calculations with realistic potentials ruled out the possibility of the ferromagnetic instability in pure neutron matter). Minimizing $\delta\epsilon$, Eq. (1), with respect to $\delta s_{\rm N}$ we find

$$\delta\epsilon_{\rm min} = -\frac{N_{\rm N}}{2(1+G_0^{\rm NN})}\left(g^{\rm PN}\right)^2\delta s_{\rm P}^2 + \delta\epsilon_{\rm P}\,. \qquad (3)$$

This formula shows, that the spin instability ($\delta\epsilon_{\rm min} < 0$) is controlled by the proton term $\delta\epsilon_{\rm P}$. If this term makes only a small contribution, the system displays a spontaneous proton polarization. There are various ways for this to happen, depending on the values of $g^{\rm PN}, G_0^{\rm NN}, G_0^{\rm PP}$ and the proton effective mass $m_{\rm P}^*$. For example if the proton-neutron spin interaction $g^{\rm PN}$ is sufficiently strong and $G_0^{\rm PP} \sim 0$ the spin instability occurs at higher densities [9]. The same effect occurs if the proton effective mass becomes sufficiently high and $G_0^{\rm PP} \sim 0$ since then the change in the proton kinetic energy due to polarization is small. In an extreme case of localized protons $\delta\epsilon_{\rm P} = 0$. Clearly, the behaviour of proton impurities is crucial for the spin properties of the system. The possibility of localization of proton impurities was considered in Ref. [13]. One should notice that microscopic calculations of the spin properties of proton-contaminated neutron matter face the problem that various phenomenological potentials strongly differ in the σ and $\sigma\tau$ channels (*cf.* Fig. 20 in Ref. [7]). Here we assume that there exists a range of densities in which $\delta\epsilon_{\min} < 0$ and we study phenomenological consequences of this assumption for neutron stars. The data on magnetic fields of neutron stars will be used to constrain parameters of the model.

Assuming that protons are fully polarized we find the magnetization in the form

$$M = \left[-\frac{g^{\rm PN} N_{\rm N}}{1 + G_0^{\rm NN}} \mu_{\rm N} + \mu_{\rm P} \right] n_{\rm P} \, . \qquad (4)$$

The quantity in the parenthesis is the effective magnetic moment per one proton. At low densities it is close to the bare proton magnetic moment $\mu_{\rm P}$, whereas at higher densities it changes sign and becomes parallel to the neutron magnetic moment $\mu_{\rm N}$. The reversal of the direction of the effective magnetic moment depends crucially on the sign of $g^{\rm PN}$, since from minimization of $\delta\epsilon$, Eq. (1), one finds $\delta s_{\rm N} \sim -g^{\rm PN} \delta s_{\rm P}$. Hence for negative values of $g^{\rm PN}$ the induced neutron spin excess points in the same direction as the proton spin density. In Fig.1 we show the magnetization, Eq. (4), as a function of the neutron density for $g^{\rm PN} = -2.5$ fm^2 and the FPR proton fraction (solid line) and also for a constant proton fraction $x = 0.05$ (dashed line). The magnetization changes sign at $n_r \approx 0.48$ fm^{-3}. For the FPR proton fraction magnetization vanishes above 0.9 fm^{-3}. One can easily imagine that the dipole magnetic field of the neutron star will reflect this behaviour of the magnetization.

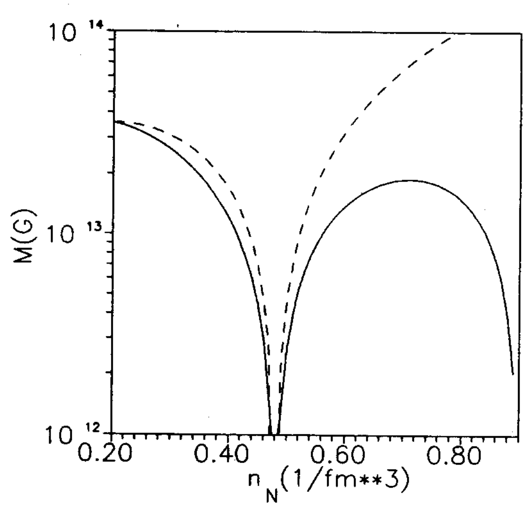

Fig. 1. The magnetization of the neutron star matter as a function of neutron density. The solid line is for the FPR proton fraction. The dashed line corresponds to a constant proton fraction $x = 0.05$.

Our model contains three parameters. The first one is the proton-neutron spin interaction $g^{\rm PN}$. It determines the density n_r at which the magnetization vanishes. We use the value $g^{\rm PN} = -2.5\ {\rm fm}^2$ which is 25% higher, than the value of Ref. [10]. The two other parameters are the critical densities $n_{\rm l}$ and $n_{\rm u}$ which limit the density range in which the magnetic phase exists. As far as the upper limit $n_{\rm u}$ is concerned a natural choice for the FPR equation of state is $n_{\rm u} = 0.9\ {\rm fm}^{-3}$, a density at which the proton fraction vanishes. This limit can be however lower, since at very low x the core temperature may exceed the Curie temperature. The lower critical density $n_{\rm l}$ should be determined by the nucleon Hamiltonian. Here we shall treat both critical densities as adjustable parameters and show predictions for a few values of $n_{\rm l}$ and $n_{\rm u}$.

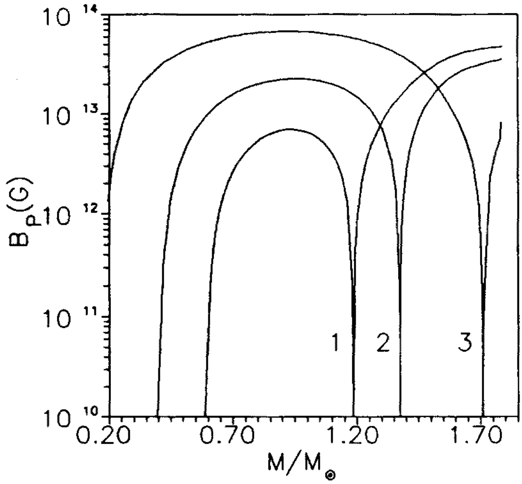

Fig. 2. The surface magnetic field as a function of the neutron star mass for the FPR equation of state. The curves labelled 1, 2 and 3 correspond to critical density $n_{\rm l}$ equal to $0.40\ {\rm fm}^{-3}$, $0.37\ {\rm fm}^{-3}$ and $0.30\ {\rm fm}^{-3}$, respectively.

The magnetic field at the surface of the star is obtained by solving the Tolman–Oppenheimer–Volkoff equations for the FPR equation of state and integrating the magnetization over the polarized core. Using the radius R of a given star and its magnetic moment $\mathcal{M}$ we calculate the surface magnetic field at the magnetic pole $B_{\rm P} = 2 \mid \mathcal{M} \mid /R^3$. The magnetic field is shown in Fig. 2 as a function of the star mass for three values of the critical density $n_{\rm l}$ and for $n_{\rm u} = 0.9\ {\rm fm}^{-3}$ with the FPR $x(n)$. Neutron stars with central densities below $n_{\rm l}$ are nonmagnetic. Neutron stars with central densities $n_{\rm l} < n_c < n_r$ have magnetic moments increasing with the mass. If the central density passes n_r, there appears an oppositely magnetized inner core, and the total magnetic moment of the star decreases and so does the surface magnetic field. The maximum for all curves occurs at $M_r \sim 0.94\, M_\odot$, which corresponds to $n_c = n_r$. The field decreases until the mass reaches the value M_z, which corresponds to the polarized core with zero total magnetic moment and the magnetic field vanishes for M_z. This mass depends on n_l. For the three values of n_l in Fig. 2, 0.30 fm^{-3}, 0.37 fm^{-3}, and 0.40 fm^{-3} we find M_z equal, respectively, to: 1.71 $M_\odot$, 1.375 $M_\odot$, 1.19 $M_\odot$. For higher neutron star masses the inner core contributes more and the magnetic moment of the star starts to increase again, albeit in the opposite direction.

One can notice that the abrupt change of the magnetic field from 10^{12} G to zero occurs over a narrow neutron star mass range $M_z - M_r$ which is of the order of 0.1 $M_\odot$. This behaviour is, generally, consistent with the above picture of the evolution of the neutron star magnetic field. If the initial pulsar mass corresponds to the field a few times 10^{12} G then accretion of a few tenths of solar mass leads to a significant decay of the magnetic field. The pulsar then evolves exactly as in the model of Shibazaki *et al.* [6]. One should however notice that if the accretion exceeds a certain amount, which for the initial mass equal to M is $\Delta M = M_z - M$, the magnetic field starts to increase again very rapidly. One can argue that this is exactly the case of the neutron star in an X-ray binary 4U 1627-27 which, as was pointed out by Verbunt *et al.* [14], accreted a lot of matter but still retains a strong magnetic field.

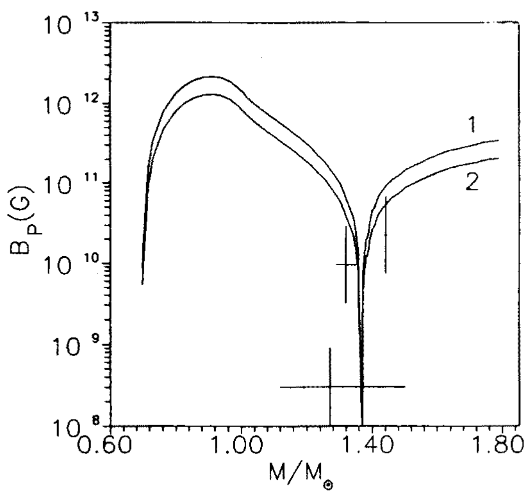

Fig. 3. The same as in Fig. 2 for $n_l = 0.43$ fm^{-3} and $n_u \approx 0.54$ fm^{-3}. The curve 1 is for the FPR proton fraction and the curve 2 corresponds to the magnetization of Fig.1 (solid line) scaled by a factor 0.6.

Recently new measurements of the mass of two millisecond binary pulsars were reported: Wolszczan [15] has determined the mass of the 37.9 ms pulsar PSR1534+12 to be 1.32±0.03 $M_\odot$ and Ryba and Taylor [16] have determined the mass of the 5.36 ms pulsar PSR 1855+09 to be $1.27^{+0.23}_{-0.15}\,M_{\odot}$. This together with the very precise determination of the mass of the pulsar PSR1913+16, which is $1.442 \pm 0.003\,M_{\odot}$ [17] allows for a more precise comparison of our model with the data. Magnetic fields of these pulsars are respectively $10^{9.98}$ G, $10^{8.48}$ G and $10^{10.35}$ G. In Fig. 3 we show these values together with an (arbitrary) error bar for the magnetic field amounting to the factor of three uncertainty which should account for the unknown deviations of the pulsar radiation law from the magnetic rotator formula. The curves correspond to $n_{\rm l} = 0.43$ fm^{-3} and $n_{\rm u} \approx 0.54$ fm^{-3}. For the curve 1 the FPR proton fraction is used. We also show results corresponding to scaling down the magnetization of Fig. 1 by a factor of 0.6 (curve 2). One should notice that in order to move closer to the data points we used a rather thin shell of magnetized matter. The critical densities used for the curve 2 in Fig. 2 give the same value of M_z but the slope of the field near zero is too steep. We have not tried to produce the best fit to the data. We rather present here some examples which show, that one can reasonably well account for the pulsar magnetic fields within a simple model. A detailed analysis of neutron star magnetic fields in the polarized proton core model is presented elsewhere.

In summary, the polarized proton core model we presented, possesses many features which phenomenologically describe the neutron star magnetic field data. The model gives the right order of magnitude of the pulsar magnetic field. It can explain the accretion-induced decay of the pulsar magnetic field. The main prediction of the model is that the pulsar magnetic field is a unique function of its mass. For the millisecond pulsars the model predicts their masses to be very close to each other. In particular the masses of the pulsars with magnetic field below 10^9 G are essentially identical and equal to $1.37 \pm 0.12\,M_{\odot}$. This is a unique prediction of the polarized proton core model, which can be used to distinguish it from other models such as *e.g.* the one based on the thermomagnetic effect in the crust [18]. There are also important implications of the model for the properties of dense matter. The change of sign in the magnetization, which is crucial for our explanation of the neutron star magnetic field decay, produces the welcome effect only if the critical densities satisfy the relation $n_{\rm l} < n_r < n_{\rm u}$. This can thus constrain models of the relevant spin-dependent nucleon interactions.

Let us mention finally, that a quark core which could be present in the heaviest neutron stars, could also contribute to the magnetic moment of the star, since the quark matter of low densities is likely to possess broken chiral symmetry and can be spin-ordered with nonzero magnetization [19]. This should be the case for the X-ray pulsar 4U0900-40 whose mass has a lower limit of $1.55\,M_{\odot}$ [20].

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