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On the origin of millisecond pulsars

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Abstract. The evolution of a neutron star entering a low-mass binary system is studied in the frame of the so called "standard" evolutionary model. We consider the evolution under the assumption that the magnetic field is of crustal origin. It is shown that millisecond pulsars can be formed in a natural way from neutron stars with more or less typical parameters in the course of evolution of such systems.

Key words: pulsars – stars: neutron – stars: magnetic fields – X-rays: stars

1. Introduction

Most of the known pulsars are single and located in the disc of our Galaxy. Their spin period and surface magnetic field strength are typically ranged from 0.1 to 5 s and from 10^{11} to 2×10^{13} G, respectively. There exists, however, a group of pulsars called millisecond pulsars with essentially shorter spin periods, $P \sim 1 - 10$ ms (for more details see Phinney & Kulkarni 1994). Typically, the magnetic field of these pulsars ($B \sim 10^8 - 10^9$ G) is substantially weaker than the standard pulsar field. This group is characterized by the high incidence of binaries: about half of the known millisecond pulsars are in binaries, whereas only $\sim 3\%$ of all pulsars are in binaries. The high abundance of binaries indicates that binarity plays an important role in the formation of millisecond pulsars. These low magnetic field and short period pulsars are believed to be old neutron stars "recycled" during a mass transfer phase in low-mass X-ray binaries (Alpar et al. 1982). In most of the binaries with millisecond pulsars, the companion itself is a star near the endpoint of its nuclear evolution (a white dwarf), indicating that in a preceding phase it was a giant star which was transfering matter to the neutron star. An intensive mass transfer in these objects ensues probably as a result of Roche-lobe overflow and may be very extended.

The evolution of a neutron star in low-mass binaries may be very long and complex since even the main-sequence lifetime of a companion exceeds 10^9 yr. The neutron star experiences the influence of the secondary practically during its whole evolution with the exception of a relatively short period just after the explosion. Initially, when the secondary evolves on the main-sequence, this influence is caused by the interaction with the stellar wind. Later on, when the secondary fills its Roche-lobe, the interaction becomes much more important and may drastically change the thermal, spin and magnetic evolution of the neutron star. The mass transfer phase is usually identified with the low-mass X-ray binaries (LMXBs). In the course of mass transfer, the majority of LMXBs (with the exception of a very few) do not exhibit pulsed X-ray emission that suggests their neutron stars being weakly magnetized and makes LMXBs plausible progenitors of the millisecond pulsars (see, e.g., Bhattacharya & van den Heuvel 1991, Phinney & Kulkarni 1994).

It is generally believed that evolutionary transformations caused by the interaction of the neutron star with the plasma of a companion in a low-mass binary result in the formation of a radiopulsar with a spin period and a surface magnetic field similar to those of millisecond pulsars. In the present paper, we consider these evolutionary transformations for the neutron star model with only a crustal magnetic field. The goal of our study is to show that, in the frame of this scenario, millisecond pulsars can be formed in a natural way from neutron stars with typical parameters under the assumption that their magnetic fields are of crustal origin.

2. Description of the model

Calculations presented here are performed for the $1.4 M_{\odot}$ neutron star model with the equation of state of Pandharipande and Smith (1975). This equation is a representative of stiff equations of state with a low central density and a massive crust. For this model, the stellar radius is ≈ 16 km and the crust thickness is ≈ 4.2 km (we assume the crust bottom to be located at the density 2×10^{14} g/cm^3). We assume the so called standard cooling scenario for the neutron star (see Van Riper 1991). This scenario corresponds to a star with normal npe-matter in the core and with standard neutrino emissivities. Our choice of the model is based on the analysis of the magnetic and spin evolution of

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isolated neutron stars done by Urpin & Konenkov (1997). According to this study, the neutron star models with equations of state stiffer than that of Friedman & Pandharipande (1981) and with standard cooling are most suitable to fit the observational data on single radiopulsars.

We consider the evolution of the neutron star assuming that its magnetic field is originally anchored in the crust. This field may be created by some mechanism either in the course of collapse or soon after the neutron star is born. The evolution of the crustal magnetic field is governed by the induction equation,

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{B} \right) + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) \, , \quad (1)$$

where σ is the conductivity and $\boldsymbol{v}$ is the velocity of material flux. Since we consider the behaviour of the field in deep solid layers of the crust, the velocity $\boldsymbol{v}$ may be caused only by the flux of the accreted matter throughout the crust and is approximately radial, $\boldsymbol{v} = -\boldsymbol{e}_r \dot{M}/4\pi r^2 \rho$ where $\dot{M}$ is the accretion rate and ρ is the density. At the neutron star surface $r = R$, the solution has to satisfy the standard boundary condition for a dipole field. Concerning the boundary condition at the crust-core boundary ($\rho = 2 \times 10^{14}$ g/cm^3), we assume the core of the neutron star to be superconductive, thus the magnetic field cannot penetrate into the core.

The conductive properties of the crust are determined by the scattering of electrons on phonons and impurities. Scattering on phonons dominates the transport processes at relatively high temperature and low densities,

whereas scattering on impurities gives the main contribution to the conductivity at low temperature and large densities. The phonon conductivity depends on the temperature, decreasing when T increases, thus the rate of the field decay is sensitive to the thermal evolution of the neutron star. The impurity conductivity is practically independent of the temperature but its magnitude is determined by the so called impurity parameter, Q. We use the numerical data for the phonon conductivity obtained by Itoh et al. (1993) and a simple analytical expression for the impurity conductivity derived by Yakovlev & Urpin (1980).

The conductive properties of the crust depend also on its chemical composition which, unfortunately, is rather uncertain in neutron stars. The dependence of σ on the composition is less significant during the early evolution, however, it may be more important during the late evolution. In our calculations, we adopt a simple model assuming that the crust is composed of nuclei processed in various nuclear transformations in accreting neutron stars (see Haensel & Zdunik 1990).

According to the standard scenario of the evolution, the neutron star can be processed in four main evolutionary phases.

Phase I. During this phase, the neutron star does not practically feel the influence of its companion thus the magnetic, thermal and spin evolution follows exactly that of an isolated star. The magnetic field decay is driven by equation (1) with $v = 0$. We use the time dependence of T from the standard cooling model as given by Van Riper (1991) for $1.4 M_\odot$ neutron star. Since the wind plasma of the companion does not interact with the neutron star magnetosphere, the spin evolution during the phase I is determined by magnetodipole radiation (Ostriker & Gunn 1969). The phase I lasts while the wind plasma is stopped by the pressure of magnetodipole radiation behind the radius of gravitational capture. The stopping radius, R_s, is determined by the balance between the dynamical pressure of the wind and the radiative pressure of magnetodipole waves. The wind pressure is $\sim \rho_w V_w^2$ where ρ_w and V_w are the density and velocity of the wind plasma, respectively. The density, ρ_w, at the distance s from the secondary may be estimated as $\rho_w \approx \dot{M}_0/4\pi s^2 V_w$ with $\dot{M}_0$ being the rate of mass loss of the secondary. The pressure of the magnetodipole radiation at the distance R_s from the neutron star is $\sim (1/4\pi R_s^2)(B_s^2 R^6 \Omega^4/6c^4)$ where Ω is the spin angular velocity of the neutron star. Equating these pressures at the nearest to the neutron star point (where $s = a - R_s$, a is the separation between the stars) and introducing the rate of gravitational capture of the wind plasma, $\dot{M}_g \approx \dot{M}_0 (R_G/2a)^2$ if $R_G < a$, $R_G \approx 2GM/V_w^2$ is the radius of gravitational capture (Bondi 1952), one has

$$R_s = a \left[1 + 4a \left(\frac{3c^4 V_w \dot{M}_g}{2B_s^2 R^6 \Omega^4 R_G^2} \right)^{1/2} \right]^{-1} . \quad (2)$$

While $R_s > R_G$, the wind matter cannot be captured by the neutron star and does not interact with the magnetosphere. In our model, the condition $R_s = R_G$ determines the transition from the phase I to the phase II.

Phase II. When the neutron star spins down or its magnetic field weakens to such an extent that $R_s < R_G$, the pressure of magnetodipole radiation cannot further prevent a fraction of the wind plasma from being captured by the neutron star. This fraction can directly interact with the magnetosphere, however, the spin is rather fast yet and the magnetosphere acts as a propeller, ejecting the wind matter. Since accretion is prohibited, the thermal and magnetic evolution of the neutron star does not differ from that of an isolated star. The spin evolution departs, however, from magnetodipole braking because a fraction of the spin angular momentum of the neutron star is transferred to the ejected wind matter. It is usually assumed that the flux of matter interacts with the magnetosphere at the Alfven radius, R_A. If the neutron star rotates rapidly and its angular velocity is larger than the Keplerian angular velocity at the Alfven radius, $\Omega_K(R_A)$, the wind matter has to be expelled by the magnetosphere (Illarionov & Sunyaev 1975). To be expelled, the wind matter should get the angular momentum larger than the Keplerian one. Therefore, the rate of the angular momentum loss, $\dot{J}_p$, may be estimated as $\dot{J}_p \simeq 4\pi R_A^4 \rho_w \Omega_K v_r$ where v_r is the radial velocity of the accreting flow near the magnetospheric boundary. Then, the spin-down rate of the neutron star is

$$\dot{P} \simeq \frac{P^2 \dot{J}}{2\pi I} \simeq \beta P^2 B^{2/7} \dot{M}_g^{6/7} \, , \quad (3)$$

where $\beta = (GMR^2/8)^{3/7}/\pi I$. The spin slows down until the angular velocity becomes comparable to $\Omega_K(R_A)$. The critical period, P_{eq}, which determines the end of the "propeller" phase and the transition to the phase III can be obtained from the condition $\Omega = \Omega_K(R_A)$,

$$P_{eq} = \frac{18.6 B_{12}^{6/7}}{\dot{M}_{-10}^{3/7}} \; s \qquad (4)$$

where $\dot{M}_{-10} = \dot{M}/10^{-10} M_\odot \mathrm{yr}^{-1}$ and $B_{12} = B/10^{12}$ G (in the case of the "propeller" phase, $\dot{M}$ has to be replaced by $\dot{M}_g$). Equation (4) determines the so called spin up line in the B - P plane.

Phase III. During this phase, accretion from the stellar wind is allowed and nuclear burning of the accreted material causes heating of the neutron star interior and induces the accretion-driven field decay. Since accretion from the wind in a binary cannot be exactly spherical, the accreting matter likely carries some amount of the angular momentum to the neutron star and, due to this, the neutron star can experience spin up to a bit shorter period (see Geppert et al. 1995). Probably, a balance may be reached in spin up and the rate of the field decay, thus the neutron star slides down the corresponding spin-up line (see, e.g., Bhattacharya & Srinivasan 1991). This evolution lasts until either the companion fills its Roche-lobe (and the neutron star enters the phase IV) or the magnetic field becomes too weak to maintain a balance in spin up and the rate of the field decay.

During the phase III, the field decay is driven by equation (1) with $\boldsymbol{v} \neq 0$. The thermal evolution of accreting neutron star has been a subject of study for several papers (see, e.g., Fujimoto et al. 1984, Zdunik et al. 1992). It was argued that, after a relatively short initial stage, the temperature within the neutron star reaches a steady state which depends on the accretion rate. For the phase III, we use the crustal temperature calculated by Zdunik et al. (1992).

The angular momentum carried by the accreted wind matter can be estimated assuming that the angular momentum at the magnetospheric boundary is characterized by its Keplerian value, $\rho \Omega_K R_A^2$, multiplied by some "efficiency" factor ξ. This factor is ~ 1 if the accreted wind matter forms a Keplerian disc outside the magnetosphere. If the disc is not formed, the angular momentum is much smaller than the Keplerian one, and likely $\xi \sim 0.1 - 0.01$. The rate of the angular momentum transfer from the wind to the neutron star is $\simeq \xi \cdot 4\pi R_A^4 \rho \Omega_K v_r$ and, hence, the corresponding spin-up rate is

$$\dot{P} \simeq -\xi \beta P^2 B^{2/7} \dot{M}^{6/7} \, . \qquad (5)$$

If the magnetic field becomes very weak, $\dot{P}$ is small and accretion cannot maintain a balance in the spin up and field decay rates, thus the neutron star can leave the spin-up line.

Phase IV. After the secondary fills its Roche-lobe, accretion onto the neutron star is strongly enhanced and heating of the crust leads to a rapid field decay. In low-mass binaries, accretion due to Roche-lobe overflow can probably last as long as $10^7 - 10^8$ yr. The magnetic field decay is governed by equation (1) with $\boldsymbol{v} \neq 0$. The thermal structure of accreting neutron stars has been calculated by Fujimoto et al. (1984) for the accretion rate $\dot{M} = 3 \times 10^{-10} M_\odot$/yr and by Miralda-Escude et al. (1991) for $\dot{M}$ within the range $10^{-10} \geq \dot{M} \geq 10^{-11} M_\odot$/yr. We matched their results and slightly extrapolate the obtained dependence in order to estimate T for $\dot{M} \sim 10^{-9} M_\odot$/yr.

During the phase IV, the accreted matter forms likely the Keplerian disc outside the neutron star magnetosphere. Therefore, the spin-up rate is given by equation (5) with the "efficiency" parameter $\xi \sim 1$. The neutron star spins up in accordance with these equations until it approaches the spin-up line corresponding an enhanced accretion rate. Probably, the accretion rate has to be reduced a bit when the neutron star reaches the spin-up line (Bhattacharya & Srinivasan 1991) but, nevertheless, the field continues to decay due to the accretion-driven mechanism. During the further evolution, a balance should be reached in spin up and the rate of the field decay like the case of accretion from the wind. Due to this balance, the neutron star slides down the corresponding spin-up line with the rate which is determined by the field decay. In reality, the evolution on the spin-up line may be very complicated but, in our calculations, we will adopt a maximally simplified model. Namely, we will neglect a possible difference in the accretion rate before and after the neutron star reaches the spin-up line. Some decrease of the accretion rate cannot probably change drastically the internal temperature because, at high accretion rates, the temperature depends relatively weakly on the accretion rate. Note that in our model, the neutron star slides down the corresponding spin-up line with the maximal rate but, in reality, the evolution will be slower. The star can leave the spin-up line either if accretion is exhausted or if the field becomes too weak to maintain a balance in spin up and the field decay.

3. Numerical results

Calculations have been performed for a wide range of the parameters characterizing both the initial magnetic configuration and the crust. The impurity parameter, Q, is assumed to be constant throughout the crust during the whole evolution and to range from 0.001 to 0.1. The initial spin period is $P_0 = 0.01$ s. We assume that the magnetic field is initially confined to the outer layers of the crust with densities $\rho \leq \rho_0$. Calculations are performed for ρ_0 ranging from 4×10^{11} to 10^{13} g/cm^3. These values correspond to the depth from the surface $\approx$820 and 1100 m, respectively. The choice of ρ_0 is imposed by a comparison of the calculated magnetic and spin evolution of isolated neutron stars with the available observational data on P and $\dot{P}$ for radiopulsars (see Urpin & Konenkov 1997). The initial surface field strength, B_0, is taken within the range $10^{13} \geq B_0 \geq 10^{11}$ G. Calculations are performed for the duration of evolution before Roche-lobe overflow, t_{ms}, as long as $10^9 - 10^{10}$ yr. During this long time, the accretion rate onto the neutron star is determined by both the parameters of stellar wind and separation between the stars, and may generally vary within a wide range. In calculations, we assume $\dot{M} = 10^{-13} - 10^{-17} M_\odot$/yr; the same value is also used for $\dot{M}_g$ during the propeller phase. We also suppose V_w = 500 km/s for the wind velocity, and $a = 5 \times 10^{12}$ cm for the separation between the stars. The efficiency parameter, ξ, is taken to be equal 0.1. Note, however, that our calculations indicate a weak sensitivity of the evolution to the particular choice

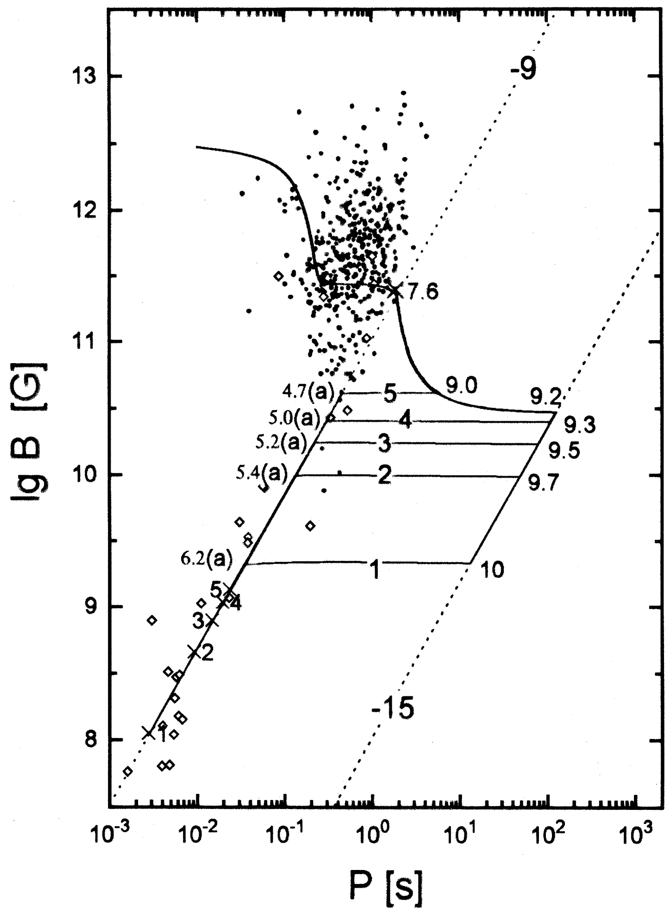

Fig. 1. The evolutionary tracks of the neutron star for a different duration of the evolution before Roche-lobe overflow, t_{ms} = 10^{10} (curve 1), 7×10^9 (2), 5×10^9 (3), 3×10^9 (4), and 2×10^9 yr. The initial field is $B_0 = 3 \times 10^{12}$ G, the initial density penetrated by the field is $\rho_0 = 10^{12}$ g/cm^3, Q = 0.03. The rates of accretion from the stellar wind and due to Roche-lobe overflow are 10^{-15} and $10^{-9} M_\odot$/yr, respectively. The duration of the phase IV is 10^8 yr.

of ξ. After the secondary fills its Roche-lobe, calculations are performed for $\dot{M} = 10^{-9} - 10^{-10} M_\odot$/yr.

Fig. 1 represents, as a characteristic example, the evolutionary tracks for different values of t_{ms}. More examples of tracks calculated for a wide range of parameters have been given by Urpin, Geppert & Konenkov (1997). For convenience, we also plot the observational data on the B-P distribution of isolated (dots) and binary (open squares) pulsars taken from the catalogue by Taylor, Manchester & Lyne (1993). The dotted lines represent spin-up lines for the accretion rate $\dot{M} = 10^{-15}$ and $10^{-9} M_\odot$/yr (numbers near these lines label the logarithm of the accretion rate). Numbers near the tracks indicate the logarithm of the neutron star age in the corresponding point; numbers with the label (a) mark the time required from the beginning of accretion to reach the spin-up line. The large cross marks a transition to the propeller phase, small crosses with the number of a track mark the endpoint of calculations.

The neutron star experiences typically all evolutionary transformations outlined by the standard scenario. The only exception is the model 5 with a short duration of pre-Roche-lobe evolution ($t_{ms} = 10^9$ yr). This model evolves from the propeller phase to the phase IV missing the wind accretion. For the models 1-4, the duration of first two phases is obviously the same, $\sim 1.6 \times 10^9$ yr. The "isolated pulsar" phase lasts $\approx$ 40 Myr, and by the end of this short phase, the field strength is reduced by a factor ≈ 10. Due to magnetodipole radiation, the neutron star spins down to $P \sim 2$ s. After $\approx$ 40 Myr, the field and spin are reduced sufficiently for the neutron star to work as a propeller. The propeller phase ends when the star reaches the spin-up line corresponding to accretion from the wind (for the models 1-4) or the secondary fills its Roche lobe (the model 5). During the phase II, the field is also reduced by a factor ~ 10 like during the much shorter phase I and is still sufficiently strong, $B \sim 3 \times 10^{10}$ G, after 1.6×10^9 yr of evolution. To the end of the phase II, the spin slows down drastically for the models 1-4, $P \sim 10^2$ s. Note that the spin period at the end of the phase II is much shorter for the model 5, $P \sim 8$ s. A further evolution on the spin-up line is completely determined by the rate of the field decay. However, the decay is rather slow because the rate of accretion from the wind is low and heating caused by such accretion cannot decrease essentially the crustal conductivity. The wind accretion phase is longest for the models 1-2 whereas the propeller phase is longest for the models 4-5. For the model 3, the duration of the phases II and III is approximately the same. The field can be reduced up to ≈ 20 times depending on t_{ms} but, nevertheless, it may be still rather strong ($B \sim 3 \times 10^{10} - 2 \times 10^9$ G) when the secondary fills its Roche lobe.

An enhanced accretion results in a fast spin up of the neutron star thus it approaches the spin-up line on a short time-scale $\sim 10^4 - 10^6$ yr depending on the field strength. This time-scale is too short for the field to decay, therefore, the star moves almost horizontally during this period. In contrast to the wind accretion phase, the decay may be fast under the influence of the accretion-driven mechanism which is much more efficient for a heavy mass transfer. During the phase IV, the magnetic field decreases by a factor $\sim 20 - 30$ thus, when accretion is exhausted, the neutron star can work as a pulsar with a weak magnetic field, $B \sim 10^8 - 10^9$ G and a short period, $P \sim 3 - 20$ ms.

In Fig.2, we plot the surface magnetic field and spin period at the end of Roche-lobe overflow versus the total amount of accreted mass. For convenience, we show the dependences for the cases with a relatively high ($\dot{M} = 10^{-9} M_\odot$/yr) and low ($\dot{M} = 10^{-10} M_\odot$/yr) accretion rate during the phase IV. For the model presented, the field is of the order of 2×10^{11} G when the secondary fills its Roche lobe. This field seems to be rather strong thus the neutron star can probably exhibit X-ray pulsations at the beginning of Roche-lobe accretion. Note, however, that for other values of the parameters (see Urpin, Geppert & Konenkov 1997) the field at the end of the wind accretion phase may be much weaker thus the star certainly cannot work as a pulsating X-ray source.

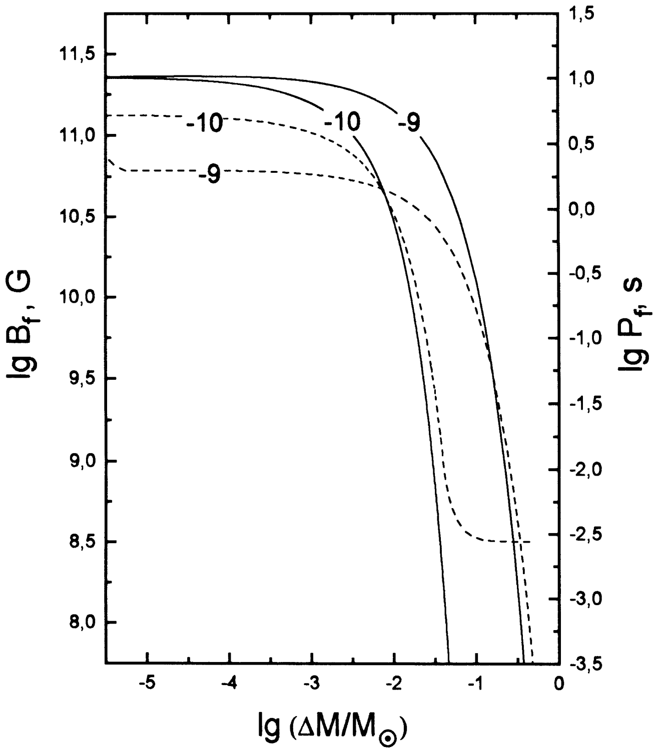

Fig. 2. The dependence of the surface magnetic field, B_f (solid lines), and spin period, P_f (dashed lines), at the end of Roche-lobe overflow on the total amount of accreted mass. The initial parameters are: $B_0 = 10^{13}$ G, $\rho_0 = 10^{13}$ g/cm^3, $Q = 0.01$. The duration of evolution before Roche-lobe overflow is $t_{ms} = 3\times10^9$ yr. The rate of accretion from the wind is $10^{-15} M_\odot$/yr. Curves are shown for two values of the accretion rate during the phase IV, $\dot M = 10^{-10}$ and $10^{-9} M_\odot$/yr (labels near indicate the logarithm of $\dot M$.

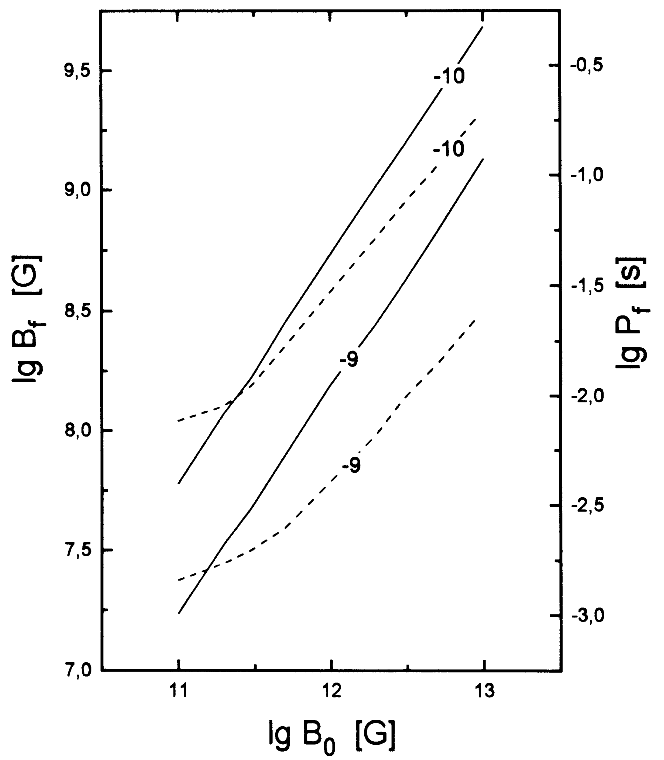

Fig. 3. The dependence of the final field strength (solid lines) and spin period (dashed lines) on the initial magnetic field, B_0. Parameters are the same as in Fig.1. The duration of pre-Roche-lobe and accretion phases is 5×10^9 and 10^8 yr, respectively.

It is seen from Fig.2 that the final field strength as well as the final period is not determined by the total accreted mass alone. The accretion-driven mechanism results in the field decay which depends on both the accretion rate and the duration of the accretion phase or, in other words, on the accretion rate and the amount of accreted mass (Urpin & Geppert 1995). The lower the accretion rate, the weaker the final field strength at a given ΔM. In order to accrete the same ΔM, the neutron star requires 10 times longer time at $\dot M = 10^{-10} M_\odot$/yr than at $\dot M = 10^{-9} M_\odot$/yr whereas the temperature is only by a factor ~ 2 larger for higher $\dot M$. An increase of the temperature and a corresponding decrease of the conductivity lead obviously to a faster decay in the case of the high accretion rate but, at a given $\dot M$, this faster decay operates during a much shorter time thus B_f turns out stronger for a higher accretion rate at the same amount of accreted mass. If accretion lasts sufficiently long, the field strength and the spin period can approach the values typical for millisecond pulsars, $B_f \sim 10^8 - 10^9$ G and $P_f \sim 1-10$ ms. For example, if $\dot M = 10^{-9} M_\odot$/yr, the neutron star requires to accrete $\approx 0.3 M_\odot$ before its field is reduced to the value 10^8 G and the rotation is spun up to $\approx 1-2$ ms. For $\dot M = 10^{-10} M_\odot$/yr, the same field strength can be reached if the neutron star accretes a substantially smaller amount of matter, $\Delta M \approx 0.03 M_\odot$. The corresponding final spin period is evidently longer in the case of a weaker accretion, $P \sim 10$ ms. Note that in the case of a weak accretion after accreting $\approx 0.03 M_\odot$ the neutron star cannot maintain a balance between the field decay and spin up and leaves the spin up line.

Evidently the final field can be weaker than 10^8 G if the accretion phase is more extended. Our simple model does not predict the existence of any kind of "residual" field strength of neutron stars. On the contrary, it is quite possible that there exist neutron stars with $B \le 10^8$ G and, most likely, such stars can be observed in binaries with very extended Roche-lobe overflow.

Fig. 3 represents the dependence of the magnetic field strength and period at the end of the accretion phase on the initial field strength, B_0. Calculations indicate a strong dependence of the final field strength on the initial one. In the considered range of parameters, this dependence can approximately be fitted by the power law with the exponent ≈ 0.9 for both high and low accretion rates during Roche-lobe overflow. It seems that in binaries with a low accretion rate ($\dot M \approx 10^{-10} M_\odot$/yr), the pulsar with the parameters within the "millisecond box" ($10^9 \ge B_f \ge 10^8$ G, $10 \ge P_f \ge 1$ ms) may be formed only if the initial magnetic field is rather weak, $B_0 \sim 2\times10^{11}$ G. If $B_0 < 2\times10^{11}$ G then the final product will be a very weakly magnetized ($B_f < 10^8$ G) and relatively rapidly spinning ($P \approx 10$ ms) neutron star. If $B_0 > 2\times10^{11}$ G then we

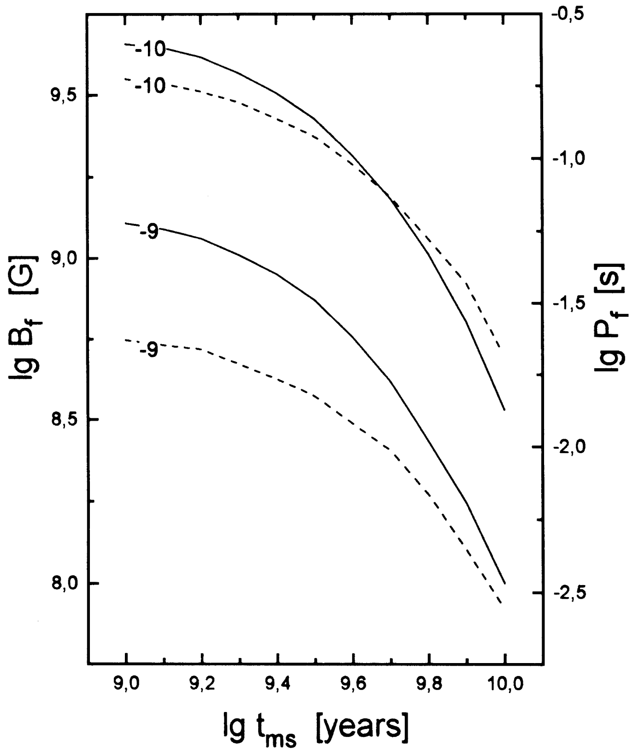

Fig. 4. The dependence of the final field strength (solid lines) and spin period (dashed lines) on the duration of evolution before Roche-lobe overflow. Parameters are the same as in Fig.1.

will observe at the end of the evolution the pulsar with a period outside of the "millisecond box" ($P > 10$ ms) and with the magnetic field $B_f \geq 10^8$ G. Binaries with a strong accretion, $\dot{M} = 10^{-9} M_{\odot}$/yr, are evidently more suitable for formation of millisecond pulsars. However, in this case, again the neutron star can be transformed to a millisecond pulsar only if the initial field is not very weak or very strong. For the considered model, the final field is larger than 10^8 G if $B_0 \geq 5 \times 10^{11}$. On the other hand, $B_f < 10^9$ G if the initial field is weaker than 5×10^{12} G. The final spin period is shorter than 10 ms if $B_0 < 5 \times 10^{12}$ G. Thus, in the case of a strong accretion ($\dot{M} \approx 10^{-9} M_{\odot}$/yr), the range of the initial field strength most suitable for the formation of "standard" millisecond pulsars is $5 \times 10^{12} > B_0 > 5 \times 10^{11}$ G. This field is typical for isolated pulsars thus it is quite possible that the progenitors of "standard" millisecond pulsars are "standard" neutron stars which, after their birth in low-mass binaries, have been processed in the above evolutionary transformations. If the initial field of the neutron star in a binary is stronger than 5×10^{12} G then, instead of a millisecond pulsar, we will observe at the end of the evolution the pulsar with stronger field and longer period. If $B_0 < 5 \times 10^{11}$ G then the final product is a rapidly spinning pulsar (with P of the order of a few ms) but with a very low magnetic field, $B < 10^8$ G.

Fig. 4 shows the final field strength and period versus the duration of evolution before Roche-lobe overflow. Evidently, both B_f and P_f are crucially dependent on the duration of this stage: the field and period decrease by factors ~ 10 and ~ 7, respectively, if t_{ms} increases from 10^9 to 10^{10} yr for both high and low accretion rates. In the case of a weak accretion due to Roche-lobe overflow ($\dot{M} = 10^{-10} M_{\odot}$/yr), the neutron star cannot evolve to the "millisecond pulsar box" under the chosen parameters: when accretion is exhausted the final period is too long in comparison with millisecond pulsars despite that the magnetic field may be of a suitable strength. On the contrary, at a high accretion rate ($\dot{M} = 10^{-9} M_{\odot}$/yr), the formation of a millisecond pulsar seems to be a plausible endpoint of the evolution. The field becomes weaker than 10^9 G if $t_{ms} > 2 \times 10^9$ yr whereas the period is shorter than 10 ms if $t_{ms} > 4 \times 10^9$ yr. Thus, if the secondary fills its Roche-lobe after 4×10^9 yr, the final product of the evolution is the neutron star with the parameters typical for millisecond pulsars. Note that even in the extremal case of a very slow evolution of the secondary when it fills the Roche-lobe after 10^{10} yr, and only after this long evolution the neutron star experiences an enhanced accretion during 10^8 yr, the magnetic field at the end of accretion may still be rather high, $B \sim 10^8$ yr. This result is in contradiction with the widely accepted point of view that the neutron star with only a crustal magnetic field cannot maintain a sufficient field strength during a long time.

4. Conclusion

We explored the evolution of the neutron star entering a close binary system with a low-mass secondary star. It is a widely accepted point of view that millisecond pulsars can be formed as a result of evolution in such binary systems (see, e.g., Bhattacharya & van den Heuvel 1991). The calculations have been performed in accordance with the scenario which implies that the neutron star has to be processed in several evolutionary phases including the heavy mass transfer phase ensued due to Roche-lobe overflow. This mass transfer may be very extended with a huge amount of mass accreted by the neutron star. In some cases the accreted mass may be as large as $0.1 - 0.5 M_{\odot}$ (see, e.g., van den Heuvel & Bitzaraki 1995).

The evolution has been considered for the neutron star model with a crustal magnetic field. Our calculations show that the decay of the crustal field may be very slow, thus the neutron star can maintain a relatively strong field during the whole evolution in a low-mass binary system. Even if the duration of the companion's life before Roche-lobe overflow is as long as 10^{10} yr and, after that, the neutron star experiences accretion with $\dot{M} \sim 10^{-9} M_{\odot}$/yr during 10^8 yr, the magnetic field can be sufficiently strong after the end of accretion.

The main goal of the present study is the evidence of the fact that millisecond pulsars can be formed from neutron stars with more or less ordinary parameters. Generally, the neutron star does not need neither particularly strong nor particularly weak initial magnetic field in order to evolve to the "millisecond pulsar box" in the B-P plane. Such an evolution does not require either extremal assumptions about the properties of the neutron star interior (presence of an exotic matter in the core, impurity content and chemical composition of the crust, etc.). The evolutionary model does not require additional assumptions which are different from the known ones about the character of evolution of the neutron star in close binary systems. The adopted evolutionary scenario turns out to be a good model for transformation of “standard” neutron stars to “standard” millisecond pulsars.

Of course, the range of parameters of newly born neutron stars may be rather wide as well as the range of parameters of low-mass binary systems (mass of the secondary, orbital period, etc.). Therefore, not all neutron stars entering low-mass binary systems will be finally transformed to millisecond pulsars. Our calculations show that the spectrum of parameters of neutron stars processed in low-mass binary systems may be very wide. For example, if the neutron star has initially the magnetic field strength above the average pulsar field strength or if the low-mass secondary is relatively massive thus the duration of its main-sequence evolution is comparatively short, then the final product of the evolution may be a pulsar with its magnetic field strength and period lying in the intermediate region of the B-P diagram between the main population of isolated pulsars and the “millisecond pulsar box” (see Fig.1). If the initial field strength of the neutron star is low or if the main-sequence evolution of the secondary is extremely long, evolutionary transformations can lead to the formation of very weakly magnetized stars with $B_f < 10^8$ G.

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