Evolution of neutron stars in high-mass X-ray binaries

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ABSTRACT
We consider the evolution of neutron stars during the X-ray phase of high-mass binaries. Calculations are performed assuming a crustal origin of the magnetic field. A strong wind from the companion can significantly influence the magnetic and spin behaviour of a neutron star even during the main-sequence life of the companion. In the course of evolution, the neutron star passes through four evolutionary phases (‘isolated pulsar’, propeller, wind accretion, and Roche lobe overflow). The model considered can naturally account for the observed magnetic fields and spin periods of neutron stars, as well as the existence of pulsating and non-pulsating X-ray sources in high-mass binaries. Calculations also predict the existence of a particular sort of high-mass binary with a secondary that fills its Roche lobe and a neutron star that does not accrete the overflowing matter because of fast spin.

Key words: accretion, accretion discs – binaries: close – stars: magnetic fields – stars: neutron – pulsars: general – X-rays: stars.

1 INTRODUCTION

By means of X-ray observations, two main classes of binary systems with neutron stars have been detected: high- and low-mass X-ray binaries (hereafter HMXBs and LMXBs, respectively). Although one component of both classes is a neutron star, they differ considerably in a number of characteristics (see e.g. Bhattacharya & van den Heuvel 1991). For LMXBs, the companion is a low-mass star of mass <1.2 M⊙, while the companions of HMXBs are luminous early-type stars with masses within the range 5–40 M⊙. The spatial distributions of these two classes are also quite different: HMXBs are concentrated towards the Galactic plane, characteristic of a relatively young population (stars with masses >10 M⊙ do not live longer than ~3 × 10⁷ yr). On the other hand, LMXBs are concentrated towards the Galactic Centre and are distributed much more widely around the Galactic plane, typical of an old stellar population (~10¹⁰ yr). The finding that LMXBs are very old objects is supported by the observation of a number of them in globular clusters. Conclusions about the surface magnetic field of the neutron star in the binary system can be drawn from X-ray time variability. While the regular X-ray pulses of many HMXBs indicate a strong field (10¹¹.5–10¹².5 G, confirmed by the observation of cyclotron lines in the hard X- and γ-ray spectra), the occurrence of X-ray bursts in LMXBs hints at their low magnetic field.

According to the evolutionary state of the companion, the orbital periods and mass transfer regimes, HMXBs can be divided into two different classes (see e.g. Bhattacharya & van den Heuvel 1991): standard massive X-ray binaries and Be/X-ray binaries. The standard systems are characterized by a very massive (>20 M⊙) evolved companion which fills (or almost fills) its Roche lobe. The orbital periods of such systems range from 1 to 10 d. Mass transfer is caused either by atmospheric Roche lobe overflow (in very close systems, Porb < 5 d) or by a strong stellar wind in wider systems. For both transfer mechanisms, the accretion rate can be as high as 10⁻³–10⁻¹ M⊙ yr⁻¹. The typical lifetime of HMXBs as strong X-ray sources does not exceed 10⁷–10⁸ yr (Savonije 1978); in the case of accretion from a stellar wind it may be as low as 10⁷ yr.

In Be/X-ray binaries, the companion star shows the emission features of a luminous early-type B star that is unevolved and deep inside its Roche lobe. The neutron star rotates in an eccentric, rather wide orbit (Porb from 15 d up to years) around the rapidly rotating Be star which loses mass by a steady stellar wind and/or by rotation-driven mass ejection from its equatorial region. Many Be/X-ray binaries show transient behaviour which is reflected by long quiet ‘off’-periods (months to years) and relatively short ‘on’-periods (weeks to months) when the system manifests itself as a strong X-ray source. Accretion from the wind can produce X-ray luminosities of ~10³²–10³⁴ erg s⁻¹. For transient sources, however, this luminosity can drastically increase (up to a value of ~10³⁶–10³⁸ erg s⁻¹, comparable to the X-ray luminosity of the standard systems) during the outburst phase of the B star and especially when, passing through periastron passage, the neutron star hits the material expelled from the Be star. The masses of the Be stars are of the order of 8–20 M⊙, on average smaller than those of the companions in standard X-ray binaries. This results in a longer lifetime of such systems, and their X-ray phase can be as long as ~10⁷ yr.

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In this paper we consider the evolution of a neutron star in a high-mass binary. Interaction with plasma lost by the secondary may be essential in high-mass binaries even if the companion is deep inside its Roche lobe, because of the strong stellar wind from massive stars ($\sim 10^{-5} - 10^{-8} M_\odot \, \text{yr}^{-1}$). Perhaps accretion from the wind is insufficient to manifest the neutron star as a bright X-ray source during the main-sequence life of the companion, but this accretion may nevertheless influence the magnetic and spin behaviour of the neutron star. Of course, when the companion fills (or almost fills) its Roche lobe and the system becomes a standard HMXB, the rate of mass transfer increases drastically and the effect of accretion becomes more appreciable.

Observations provide information on the magnetic field and spin period of neutron stars in HMXBs at different evolutionary stages. The measured periods lie within the range 0.07–835 s (Bhatta-charya & van den Heuvel 1991), much wider than that of isolated radio pulsars. Cyclotron lines have been observed in the spectra of eight stars (White, Nagase & Parmar 1995). The field strength inferred from these lines ranges from $10^{12}$ to $3.4 \times 10^{12}$ G. These fields seem to be weaker than the mean field of radio pulsars ($\sim 4 \times 10^{12}$ G), particularly if we take into account the fact that cyclotron lines provide an estimate of the polar field that is a factor of 2 higher for the dipole configuration than the equatorial field inferred from $P$ and $P$ for radio pulsars. A comparison of these data with evolutionary calculations may be a good test of the consistency of theoretical models.

In the present paper we treat the evolution of a neutron star with the magnetic field maintained by currents in the crust. This model fits well the behaviour of isolated radio pulsars (Urpin & Konenkov 1997) and neutron stars in low-mass binary systems (Urpin, Geppert & Konenkov 1998). It will be shown that the characteristics of neutron stars in HMXBs may well be understood in the framework of this model also.

The paper is organized as follows. In Section 2 we describe the adopted model. The results of evolutionary calculations are presented in Section 3. In Section 4, we give a brief summary of our results.

2 DESCRIPTION OF THE MODEL

The main-sequence lifetime of a massive star, $\tau_{\text{ms}}$, is approximately given by

$$\tau_{\text{ms}} \approx 10^{10} (M_\ast/M_\odot)^{-2.5} \, \text{yr},$$

(1)

where $M_\ast$ is the stellar mass (see e.g. Bhattacharya & van den Heuvel 1991). In high-mass binaries, the mass of a companion is typically $\approx 10 M_\odot$, and hence the main-sequence evolution lasts not longer than $3 \times 10^8$ yr. Within this time the companion loses its mass as a result of the stellar wind. The empirical expression for the rate of mass loss of O and B stars as a result of the stellar wind. The empirical expression for the rate of mass loss of O and B stars, due to Bondi (1952), has the form

$$\dot{M}_w \approx 2G M V_w^2,$$

where $M$ is the neutron star mass and $V_w$ is the wind velocity (we assume that $V_w$ is much larger than the sound speed of the wind plasma and the velocity of orbital motion). Typically, $V_w \sim 1000 \text{km} \, \text{s}^{-1}$ for massive stars, therefore $R_G = 4 \times 10^{10}$ cm for $M = 1.4 M_\odot$. Then the rate of gravitational capture is

$$M_G \approx M_s (R_G/2a)^2,$$

(3)

where $a$ is the separation between the stars. For a massive binary with $M_\ast > M$, we have

$$\left(\frac{R_G}{2a}\right)^2 \approx 10^{-3} \left(\frac{M_\ast}{10 M_\odot}\right)^{-2/3} \left(\frac{P_{\text{orb}}}{1 \, \text{d}}\right)^{-4/3},$$

(4)

where $P_{\text{orb}}$ is the orbital period. Note that for Be stars the velocity of the wind may be lower ($V_w \sim 10^7 \text{cm} \, \text{s}^{-1}$) than for O and B giants because of the specific mass loss mechanism (see e.g. Nagase 1989) and, owing to this, the fraction of captured plasma may be even higher.

For binaries with an orbital period of a few days, the neutron star may capture $\sim (10^{-3} - 10^{-6}) M_\ast$ and accrete (when accretion is allowed) $\sim 10^{-9} - 10^{-13} M_\odot$ yr$^{-1}$ even during the main-sequence evolution of the companion. This accretion rate is an order of magnitude lower, at least, than the Eddington accretion rate, and therefore the majority of high-mass binaries cannot be bright X-ray sources prior to the Roche lobe phase. Nevertheless, such accretion may have an appreciable effect on the magnetic and spin evolution of a neutron star.

The neutron star passes through different evolutionary stages in a binary system. Following Illarionov & Sunyaev (1975), these phases are as follows.

1. Phase I: the ‘isolated pulsar’ phase in which the radiative pressure is sufficient to keep the plasma of the stellar wind away from the neutron star magnetosphere; the evolution of a neutron star follows exactly that of isolated stars.

2. Phase II: the propeller phase in which the wind plasma interacts with the magnetosphere but the spin is still sufficiently fast to accelerate the infalling matter outward; the thermal and magnetic evolution of the neutron star is the same as for an isolated star, but spin-down is more efficient.

3. Phase III: the wind accretion phase in which accretion of the wind plasma is allowed; nuclear burning of the accreted material heats the neutron star (Zdunik et al. 1992) and causes accretion-driven field decay (Urpin & Geppert 1995); the neutron star can experience spin-up during this phase, owing to the angular momentum carried by the accreted material.

4. Phase IV: the enhanced accretion phase which starts when the companion fills (or almost fills) the Roche lobe; the neutron star is heated to a very high temperature, $\sim (2 - 5) \times 10^8$ K (see Fujimoto et al. 1984; Brown & Bildsten 1998); the accretion-driven field decay and spin-up are much more efficient than during phase III.

Calculations have been done with the numerical code described in detail by Urpin et al. (1998). We consider the evolution for a $1.4 M_\odot$ neutron star model with the equation of state of Pandharipande and Smith (PS; see e.g. Pandharipande & Smith 1975) and with the standard cooling scenario. Our choice is motivated by the fact that only models with sufficiently stiff equations of state (stiffer than that of Friedman and Pandharipande) and with standard cooling seem to be suitable to account for the available observational data on the magnetic evolution of isolated pulsars (Urpin & Konenkov 1997). For the PS model, the radius and crust thickness are 16.4 km and 4200 m, respectively; we assume the crust bottom to be located at a density of $2 \times 10^{14}$ g cm$^{-3}$.

Unfortunately, our numerical code does not allow us to model a highly variable evolution of transient Be/X-ray binaries. Therefore
the calculations presented here concern only standard HMXBs and those of Be/X-ray systems that do not exhibit transient behaviour. We also do not consider the late evolution of a neutron star when accretion owing to Roche lobe overflow is exhausted. Probably, the further evolution leads to a common envelope phase (van den Heuvel & Bitzarak 1995), which requires a very refined consideration of the thermal effects. We are planning to address this problem in a forthcoming paper.

3 NUMERICAL RESULTS

The evolution of the crustal magnetic field is sensitive to the initial depth penetrated by the field. We assume the magnetic field to be initially confined to the outer layers of the crust with densities $\rho \leq \rho_0$. Calculations are performed for $\rho_0$ within the range $10^{11}$–$10^{13}$ g cm$^{-3}$. These values correspond to a depth from the surface of $\approx 620$ to $\approx 1100$ m. The choice of $\rho_0$ is imposed by a comparison of the calculated evolutionary tracks of isolated neutron stars with the available observational data on $P$ and $P$ for radio pulsars (see Urpin & Donenkov 1997).

The magnetic evolution depends also on the conductive properties of the crust, which are determined (see Yakovlev & Urpin 1980) by scattering of electrons on phonons (at a high temperature and relatively low densities) and on impurities (at a low temperature and high densities). The impurity conductivity depends on the so-called impurity parameter, $Q$. The exact value of $Q$ is uncertain, but it is usually assumed that $Q \approx 0.1$. Note that, in HMXBs, a variation of $Q$ shows no appreciable effect since the crustal temperature is sufficiently high during the whole evolution and the conductivity is mainly determined by scattering on phonons.

The initial field strength and spin period are assumed to be more or less standard for young pulsars, $B_0 = 10^{12}$–$10^{13}$ G and $P_0 = 0.01$ s, respectively. However, the results are not sensitive to a variation of $P_0$. The accretion rate may vary within a wide range during the life of the neutron star. We use the same values ($\approx 10^{-9}$–$10^{-13}$ M$_{\odot}$ yr$^{-1}$) for both the wind accretion rate and the rate of gravitational capture during the propeller phase. During phase IV, the accretion rate is assumed to be higher, $M = 10^{-6}$–$10^{-3}$ M$_{\odot}$ yr$^{-1}$.

In our numerical code, the spin evolution during phases III and IV is determined by the efficiency parameter, $\zeta$. The amount of angular momentum carried by accreted matter can be estimated from the condition that the magnetospheric boundary assumes that the angular momentum is characterized by its Keplerian value multiplied by the factor $\zeta$. This factor is $\approx 1$ if the accreted material forms a Keplerian disc outside the neutron star magnetosphere. If the disc is not formed then the efficiency of spin-up is much lower and the parameter $\zeta$ is probably of the order of $0.1$–$0.01$.

In Fig. 1 we plot evolutionary tracks for the model that represents neutron stars in non-transient Be/X-binaries. We assume $\tau_{\text{ms}} = 10^5$ yr, $V_\text{w} = 10^7$ cm s$^{-1}$, $\rho_0 = 10^{13}$ g cm$^{-3}$ and $Q = 0.01$. The duration of the ‘isolated pulsar’ phase is very sensitive to the initial field strength. For $B_0 = 10^{13}$ G, this phase is extremely short (\approx 3×10^5 yr) because of fast spin-down. In the case of a weak initial field ($B_0 = 10^7$ G), the spin-down rate is lower, thus radiation can prevent the wind plasma interacting with the neutron star magnetosphere for longer. During phase I the magnetic field experiences only minor changes, whereas the spin period can increase by more than two orders of magnitude in some models. Phase II is more extended and can sometimes last until the end of the main-sequence life of the companion if the initial field is weak ($\approx 10^{12}$ G) and the accretion rate is low ($\approx 10^{-12}$ M$_{\odot}$ yr$^{-1}$). Thus, in some Be binaries, the neutron star may not pass through the X-ray phase at all (except, maybe, for relatively short outburst periods). The magnetic field at the end of the propeller phase is only a factor of $\approx 3$ weaker than the initial field for all models considered. In contrast, the spin period experiences the most dramatic changes during this phase. Owing to an efficient angular momentum loss, the neutron star spins down to very long periods \approx 100–300 s. The maximum period reached during phase II is longer for a neutron star with a stronger initial magnetic field and a lower accretion rate. One, however, that for very low accretion rates the neutron star does not have enough time to reach the maximum period during the main-sequence evolution of the companion. In the case $B_0 = 10^7$ G, the longest period is $\approx 500$ s, which the neutron star reaches at $P \approx 10^{-3}$ M$_{\odot}$ yr$^{-1}$. For $B_0 = 10^9$ G, the longest period is shorter, $\approx 30$ s, and it can be reached at a higher accretion rate, $M \approx 3 \times 10^{-12}$ M$_{\odot}$ yr$^{-1}$.

Owing to efficient propeller action, the neutron star enters the wind accretion phase with a long period but still with a strong magnetic field, $\approx B_0/3$. This field seems to be sufficient to channel accretion to the magnetic poles, and thus the neutron star can manifest itself as a long-period pulsating X-ray source at the beginning of phase III. However, nuclear burning of the accreted material heats the neutron star and accelerates the accretion-driven field decay. For the maximal accretion rate, $M = 10^{-10}$ M$_{\odot}$ yr$^{-1}$, the field strength at the end of the main-sequence evolution is $B \approx 10^{11}$ and $\approx 10^{10}$ G for $B_0 = 10^{13}$ and $10^{12}$ G, respectively. These values are relatively low and, perhaps, pulsations of X-ray emission may be smoothed (or even unobservable) at the end of the evolution, particularly for the case $B_0 \leq 10^7$ G. For a lower accretion rate, the decay is less appreciable, and the magnetic field can channel accretion to the poles up to the end of the wind accretion phase. The angular momentum carried by the wind plasma can spin up the neutron star. The final spin period after $10^7$ yr of evolution depends on the accretion rate and the initial field strength. This period may be short (\approx 0.3–3 s) for weakly magnetized stars with $B_0 \leq 10^{12}$ G, but it may also be rather long.
The spin period increases by factors of \(100\) and \(10\), respectively, during phase I for \(B_0 = 10^{13}\) and \(10^{12}\) G. An efficient propeller action leads to a further spin-down of the neutron star. For the model with a strong initial field, a maximum period of \(300\) s can be reached for relatively weak wind accretion with \(M \sim 10^{-13} M_\odot\) yr\(^{-1}\). For a weakly magnetized star, the spin is typically faster, and the maximum period is \(6\) s. Note that the maximum spin period may be longer in binaries with less massive companions and more extended main-sequence evolution. When the secondary fills its Roche lobe, the neutron star experiences a fast spin-up in the case of near-Eddington mass transfer, and thus it can be a slowly rotating pulsating X-ray source only for a very short time. For a low accretion rate, spin-up to the corresponding spin-up line may take longer.

In Fig. 3, we plot the evolutionary tracks of the models presented in Fig. 2. The main difference compared with Fig. 1 is a weaker field decay caused by a shorter main-sequence lifetime. The most remarkable behaviour is shown by model 5. We believe that this sort of behaviour may be typical of all weakly magnetized stars in standard binaries. Model 5 has an initial field of \(10^{12}\) G which is weakened to \(10^{11}\) G after phase I. This field is relatively weak for an efficient propeller action, therefore spin-down proceeds very slowly during phase II, and the neutron star does not pass through phase III. At the end of main-sequence evolution, the spin period is \(0.3\) s. When Roche lobe overflow starts, the plasma of the companion forms a disc around the neutron star. However, the spin angular velocity is larger than the Keplerian angular velocity at the Alfvén radius even for near-Eddington mass transfer. The transferred matter cannot penetrate through the centrifugal barrier, and accretion on to the neutron star is prohibited. Therefore, at the beginning of Roche lobe overflow, the neutron star continues to work as a propeller and to eject matter from the disc. This ‘disc propeller phase’ lasts approximately \(8 \times 10^5\) yr, while the spin period is shorter than the corresponding corotation period (\(0.67\) s). When the spin slows down to corotation, accretion is allowed and the neutron star can manifest itself as a bright X-ray source. However, the field is rather low when the disc propeller action ends (\(< 2 \times 10^{12}\) G), thus this model should exhibit a non-pulsating behaviour. It appears that such evolution may be typical of all weakly magnetized neutron stars if the wind accretion rate is \(\leq 10^{-11} M_\odot\) yr\(^{-1}\) during the main-sequence life of the companion.

Since the initial depth penetrated by the field is quite uncertain, in Fig. 4 we plot for comparison the evolutionary tracks for \(p_0 = 10^{12}\) G. The evolution is qualitatively similar to that plotted in

\begin{equation}
\log t [\text{years}] \\
\log B [\text{G}]
\end{equation}

\begin{equation}
P [\text{s}]
\end{equation}
magnetic poles and to produce regular X-ray pulsations. In contrast, the field of an initially weakly magnetized neutron star ($B_0 \lesssim 10^{12}$ G) can be reduced to a value of $\sim 4 \times 10^{10} - 2 \times 10^{11}$ G, insufficient to channel plasma during the Roche lobe phase. Thus our model explains naturally the existence of pulsating and non-pulsating X-ray sources in high-mass binaries (see e.g. Bhattacharya & van den Heuvel 1991).

The model considered can also account for a wide range of neutron star spin periods observed in high-mass binaries. Depending on the initial field strength and the rate of mass loss, the neutron star can spin down to $P \sim 10^2 - 10^4$ s during the propeller phase. In contrast, accretion can accelerate rotation to $P \sim 0.1$ s during phases III and IV, thus the range of periodicity of HMXBs should be very wide, 0.1–1000 s.

Our model predicts the existence of a particular sort of object among high-mass binaries: systems with a evolved companion filling its Roche lobe and a non-accreting neutron star. In binaries with relatively weak wind accretion, the neutron star spins down very slowly even during the propeller phase, $B_0 \lesssim 10^{12}$ G. When the companion ends its main-sequence evolution and fills the Roche lobe, the overflowing matter probably forms an accretion disc around the neutron star. However, the spin period of a weakly magnetized neutron star can be shorter than is required by the corotation condition at the magnetospheric boundary. Thus accretion turns out to be forbidden and the neutron star continues to work as a propeller. This ‘disc propeller’ phase seems to be unavoidable for neutron stars with an initial magnetic field that is not very strong. The duration of this phase ($\sim 10^2$ yr) may be comparable to the duration of the Roche lobe phase. Thus, for some systems, enhanced accretion does not start at all. If Roche lobe overflow lasts sufficiently long to spin down the neutron star, then accretion is allowed and such a system spends the rest of the Roche lobe phase as a typical HMXB.

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