The evolution of low-mass close binary systems with a compact component
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II.2. ON THE BIRTH RATES OF LOW-MASS GALACTIC BINARY RADIO PULSARS AND THEIR POSSIBLE PROGENITOR-SYSTEMS
On the birth rates of galactic low-mass binary radio pulsars and their possible progenitor systems.

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SUMMARY:

We reconsider the birth rates of galactic low-mass binary radio pulsars and their possible progenitor systems. Kulkarni and Narayan (1988) found a discrepancy between galactic low-mass binary radio pulsars and low-mass X-ray binaries of short orbital period of a factor between 300 and 2000 and for long orbital period systems of at most a factor 6. We find that the birth rates for the short orbital period systems differ by at most a factor 39, whereas the birth rates of the long orbital period systems are in reasonably good agreement. The largest sources of uncertainties are the poor statistics of the sample of binary pulsars with a low-mass companion, the estimated lifetimes of the low-mass X-ray binaries and the unknown number of progenitors of low-mass binary radio pulsars, which accrete at a super-Eddington rate. We suggest that (partial) evaporation of the secondary in a close binary may resolve (part of) the discrepancy, found for the short orbital period systems.
1. Introduction

So far, 5 galactic low-mass binary radio pulsars (LMBRPs) have been detected, including the recently discovered millisecond pulsar PSR 1957+20 (Fruchter et al., 1988). For a review on the binary radio pulsars with a low-mass companion, their formation and their evolution, see e.g. Van den Heuvel (1988). These systems consist of a neutron star (NS) and mostly a low-mass white dwarf companion (i.e. $M_2 < 0.45 M_\odot$). Some of the LMBRPs may contain hydrogen-rich components of very low mass, e.g. the system PSR 1957+20 (Fruchter et al., 1988; van den Heuvel and van Paradijs, 1988; Phinney et al., 1988). The progenitors of LMBRPs, which contain a white dwarf secondary, are thought to be the wide low-mass X-ray binaries (LMXBs), in which the low-mass companion is a (sub)giant which overflows its Roche-lobe and transfers mass onto the neutron star companion, thereby generating X-rays (see e.g. Webbink et al., 1983 thereafter WRS; Pylyser and Savonije, 1988; and references therein). Various authors described the evolution of some of the LMBRPs with the model calculations for low-mass X-ray binaries, as presented by WRS (Joss and Rappaport, 1983; Paczynski, 1983; Savonije, 1983, 1987). The single 1.5 ms pulsar, PSR 1937+21, is now believed to be the remnant of a low-mass binary system, since it has been shown that the outflow of energetic radiation of a millisecond neutron star, in a close binary system, is able to completely "evaporate" its low-mass, hydrogen-rich companion, as observed in PSR 1957+20 (Fruchter et al., 1988; van den Heuvel and van Paradijs, 1988; Phinney et al., 1988; Kluzniak et al., 1988).

During the mass transfer phase, the accreting NS acquires angular momentum from the infalling matter and it is spun up. The evolution of the spin period of an accreting NS is determined by the evolution of both the NS magnetic field and the accretion rate (e.g. Ghosh and Lamb, 1978, 1979; de Kool and van Paradijs, 1987; Pylyser, 1988). Three of the galactic LMBRPs and the single millisecond pulsar have pulse periods $< 6$ ms and very low $P$-values (see table 1), indicating low surface magnetic field strengths (i.e. $< 5 \times 10^8$ Gauss).

If the LMXBs are the sole progenitors of all the LMBRPs, the birth rates of both types of system should be equal in a steady-state situation. Van den Heuvel et al. (1986) estimate the inverse birth rate...
Table 1

The properties of the LMBRPs in the sample

<table>
<thead>
<tr>
<th>PSR</th>
<th>P (ms)</th>
<th>log P (s/s)</th>
<th>P_{\text{orb}} (days)</th>
<th>log B (Gauss)</th>
<th>d (kpc)</th>
<th>M_2^a (M_\odot)</th>
<th>age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0820+02</td>
<td>865</td>
<td>-16.0</td>
<td>1232.5</td>
<td>11.5</td>
<td>1.92</td>
<td>0.2 - 0.4</td>
<td>10^7</td>
</tr>
<tr>
<td>1831-00</td>
<td>521</td>
<td>-16.8</td>
<td>1.81</td>
<td>10.9^b</td>
<td>3.3</td>
<td>0.06 - 0.13</td>
<td>1.9 x 10^7</td>
</tr>
<tr>
<td>1855+09</td>
<td>5.36</td>
<td>-19.7</td>
<td>12.33</td>
<td>8.52</td>
<td>0.35</td>
<td>0.2 - 0.4</td>
<td>4.3 x 10^8</td>
</tr>
<tr>
<td>1937+21</td>
<td>1.56</td>
<td>-19.0</td>
<td>8.65</td>
<td>2.1</td>
<td>---</td>
<td>---</td>
<td>10^3</td>
</tr>
<tr>
<td>1953+29</td>
<td>6.1</td>
<td>-19.5</td>
<td>117.35</td>
<td>8.65</td>
<td>3.9</td>
<td>0.2 - 0.4</td>
<td>3.2 x 10^8</td>
</tr>
</tbody>
</table>

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a) Most likely mass for the secondary

b) Log B for PSR 1831-00 was calculated using the value of the period derivative given by Taylor and Dewey (1988).

for the LMXBs to be about 5.0 x 10^6 yr. If the magnetic fields of binary pulsars decay on the same timescale as that of the single radio pulsars (about 5 x 10^6 years), they would no longer be observable after about 2 x 10^7 years, and we would expect to observe no more than a few such systems in the whole Galaxy (Van den Heuvel et al., 1986). From the fact that, among the about 500 known galactic radio pulsars, five have already been observed in LMBRP-systems, an incidence of about 10^{-2} is inferred. The total pulsar population for our galaxy is estimated at about 1.5 x 10^5 (Narayan, 1987), suggesting a total number of LMBRPs of about 1500. This number exceeds, by a factor of 300 the number one expects, if the magnetic fields of binary pulsars decay continuously on timescales of the order of 5 x 10^6 years. This discrepancy can be removed if one allows for the existence of a bottom field, beyond which NS magnetic field-decay occurs on a timescale of about 10^9 yr or longer, (Bhattacharya and Srinivasan, 1986; van den Heuvel et al., 1986). Direct evidence for the existence for such a bottom field has come from the optical observations of the white dwarf companion in the binary systems PSR 0655+64 (Kulkarni, 1986) and PSR 1855+09 (Wright and Loh, 1986; Kulkarni, 1987), whose age of a few 10^9 years can be estimated from its optical colours.

Kulkarni and Narayan (1988, hereafter referred to as KN) estimated the birth rates of LMBRPs, taking various selection effects into account and assuming the above field decay model for neutron stars. They made an independent estimate of the birth rate for the LMXBs and conclude that,
for the short orbital period systems, there is (still) a discrepancy between
the birth rates of both types of system of a factor 300 to 2000. For the
long orbital period systems, they found a discrepancy of at most a factor 6.

We here reconsider the birth rates of galactic LMBRPs and their possible
progenitor systems and discuss the significance of any discrepancies found. Section 2 discusses the birth rate of the LMBRPs, and Section 3
the birth rate of the LMXBs. In Section 4 the results are summarized and possible solutions for the observed discrepancies are given.

2. The birth rate of low-mass binary pulsars

In our analysis, we restrict ourselves to the population of LMBRPs in the disk and exclude the four recently discovered sources in globular clusters. We also include the single 1.5 ms pulsar PSR 1937+21 in our sample. Until recently, evolutionary scenarios for PSR 1937+21 indicated that the progenitor system might have belonged to the group of the MXRBs (e.g., van den Heuvel and Bonsema, 1984; Bonsema and van den Heuvel, 1985). However, the recent discovery of the 1.6 eclipsing binary millisecond pulsar PSR 1957+20, which has a secondary of only .024 M⊙ (Fruchter et al. (1988)), indicates that the progenitor systems of both PSR 1957+20 and PSR 1937+21, may have been a LMXB (Ruderman et al., 1988, Van den Heuvel and van Paradijs, 1988; Phinney et al., 1988; Kluźniak et al., 1988). Some of the characteristics of our sample of LMBRPs are listed in Table 1. Because of the lack of sufficient data at this time, PSR 1957+02 is not included. We note that our sample is identical to the sample used by KN.

The method used by KN to derive birthrates for LMBRPs, was introduced by Narayan (1987), who defined a scale factor S(P,L), relating the observed pulsar distribution ρ₀(P,P,L) to the true distribution ρₜ(P,P,L). Narayan accounted for various selection effects, and allowed for a beaming factor that varies with the pulse period P, as suggested by Narayan and Vivekanand (1983). They find that for fast pulsars (P < 0.1 s) the beaming factor f(P) may be about 1.0, rather than about 0.2 (Gunn and Ostriker, 1970).
Using the method of Narayan (1987), KN calculated the birth rates of LMBRPs in more detail. They included 5 additional pulsar surveys to the four 400 MHz surveys used by Narayan (1987), in determining the scale factors. Some of the additional surveys were sensitive enough to detect millisecond pulsars. For the sample of systems given in Table 1, KN find a total inverse birth rate for the galactic population of LMBRPs of $BR^{-1} = 3.3 \times 10^4$ yr and of $2.0 \times 10^5$ yr, at the 99 percent confidence level.

KN separate the LMBRPs in 'slow' ($P_{\text{orb}} > 25$ days) and 'rapid' systems ($P_{\text{orb}} < 25$ days), and make a similar division (at an initial period $P_i$ of 3 days) of the LMXBs into slow and rapid systems. They find inverse birth rates for the slow and rapid LMBRPs of $4.5 \times 10^4$ yr and $1.3 \times 10^5$ yr, respectively.

The total birth rate, and the birth rate for the short-orbital period LMBRPs are dominated by the presence of PSR 1855+09 in the sample. The inverse birth rate derived for this pulsar is $5.7 \times 10^4$ yr (KN), whereas the total inverse birth rate for LMBRPs is $3.3 \times 10^4$ yr. KN estimate the total number of objects like PSR 1855+09 in the disk of our galaxy to be about $1.5 \times 10^5$, i.e. of the same order as the total number of single pulsars derived by Narayan (1987), which seems extremely high. The inferred birth rate for this system is so high, because PSR 1855+09 is a nearby, low luminosity pulsar (Luminosity at 400 MHz of 1.84 mJy kpc$^2$, adopting a distance of 350 pc.), which results in a very high scale factor $S(P,L)$.

However, according to Stokes et al. (1986), the incidence of millisecond pulsars among the whole pulsar population may be of the order 0.1. Since $N_{\text{total}} = 1.46 \times 10^5$ (Narayan, 1987) in our Galaxy, the inverse birth rate for PSR 1855+09 then becomes about $5.7 \times 10^5$ yr. Adopting the birth rates for the other systems from KN, the total inverse BR is then $7.1 \times 10^4$ yr and the inverse birth rate for rapid systems becomes $1.6 \times 10^5$ yr.

3. The birth rate of LMXBs.

In this Section we will use the numerical model calculations of Pilyser and Savonije (1988, hereafter referred to as PS), to derive the
birth rates for short orbital period LMXBs. The effect of magnetic braking (Verbunt and Zwaan, 1981) is included in these calculations and the initial period of the calculated systems is < 1.9 days.

3.1 The method.

In wide LMXBs (i.e. $P_{orb} > 12$ h), mass transfer is driven by the interior nuclear evolution of the donor star (WRS). According to WRS, the average mass transfer rate $\langle M \rangle$ and the final period $P_f$ as a function of the initial period $P_i$ for such systems (for $X=0.7$, $Y=0.02$), are given by:

\[
\langle M \rangle = -5.3 \times 10^{-10} \left( \frac{P_i}{\text{day}} \right) \left( \frac{M_\odot}{\text{yr}} \right) \quad (1a)
\]

\[
\log P_f = 0.73 (\pm 0.01) \log P_i + 1.28 (\pm 0.01) \quad (1b)
\]

Although Eqs. (1a) and (1b) are valid only for initial binary periods $P_i > 1.3$ d, KN assume that Eq. (1a) can also be used for systems with $0.5 \, \text{d} < P_i < 1.3$ d. Observational evidence that Eq. (1b) is not applicable for these systems, comes from the LMBRP PSR 1831-00. Indeed, the shortest final orbital period $P_f$, that can be reached in the models of WRS, is 10.5 days, which is in contradiction with the observed orbital period of 1.81 days of the LMBRP PSR 1831-00.

An upper limit to the initial period $P_i$ of LMXBs is set by the Eddington mass transfer rate, for which it is expected that X-ray detection is inhibited by the large amount of matter accreted on the NS, i.e. $P_i < 25$ d. The initial period range of $1.3 \, \text{d} < P_i < 25$ d thus corresponds to a final period distribution of $23 \, \text{d} < P_f < 217$ d.

The orbital period of PSR 0820+02 ($P_{orb} = 1232.5$ d.) indicates that its initial period is about 300 days and shows that during the previous mass-transfer phase, accretion must have been super-Eddington and the system was probably invisible as an X-ray source. De Kool and van den Heuvel (1986; see also Helfand and Becker, 1985) suggest that the progenitor-systems of LMBRPs like PSR 0820+02 can be seen as axially symmetric radio sources (ASRs, see Shaver et al., 1985; Becker and Helfand, 1985; Becker, 1985). Whether or not these observed ASRs are effectively the progenitors of LMBRPs, which accrete matter at a super-
Eddington rate we will hereafter denote these systems as ASRs.

We notice here that according to Eq. (1b), an initial period $P_i$ of 3 days (at which KN made a separation between rapid and slow LMXBs), corresponds with a final period of about 42 days. The latter period therefore correspondingly divides the sample of LMBRPs in rapid and slow systems, instead of the dividing period of 25d, used by KN. Fortunately, the sample of rapid and slow LMBRPs remains the same as in KN, and consequently, their derivation of the birth rates of the sample of rapid and slow LMBRPs remains valid.

In view of the limitations of the semi-analytical description of WRS for short orbital period systems, we decided to use the results obtained by PS, which include both the effects of gravitational radiation and magnetic braking. The initial periods of the systems in these calculations range between 0.67 and 1.91 days.

Fig. 1 presents the relation between the final period $P_f$ and initial period $P_i$ resulting from the calculations performed by PS. For comparison, the relation (1b) (WRS) is added in Fig. 1. For all $P_i < 1.6$ d, the relation obtained from PS is significantly different from WRS, clearly demonstrating the effects of magnetic braking:

$$\log P_f = 3.32 \pm 0.45 \log P_i + 0.78 \pm 0.06$$

(1c)

for $0.67 \text{ d} < P_i < 1.91 \text{ d}$.

Fig. 2 relates the mean mass-transfer rate and the initial orbital period, as derived from the calculations by PS, and can be described by:

$$\log \langle M \rangle = (3.80 \pm 0.33) \log P_i + (-9.06 \pm 0.04)$$

(1d)

for $0.67 \text{ d} < P_i < 1.91 \text{ days}$. The relation (1a) obtained by WRS is added for comparison.

In order to understand the above differences, we present in figure 3 the stellar radius as a function of the He-core mass for single stars of $0.7 M_\odot$, $1.0 M_\odot$, $1.5 M_\odot$ and a $2.0 M_\odot$. The mean stellar radius - core mass relation derived by WRS is added for comparison (dash-crossed
Figure 1: The relation between the final and initial orbital periods \( P_f \) and \( P_i \) of short orbital period LMXBs \((P_i < 1.9 \text{ d.})\), according to the numerical calculations by PS. The semi-analytical relation, derived by WRS is added for comparison. For all initial orbital periods \( P_i < 1.6 \text{ days} \), the effects of inclusion of orbital angular momentum loss, due to magnetic braking, in the results of the numerical calculations and the limitations of the description for the evolution of LMXBs as provided by WRS, is clearly demonstrated.

Figure 2: The relation between the mean mass transfer rate \( \langle M \rangle \) and the initial orbital period of short orbital period LMXBs \((P_i < 1.9 \text{ day})\). For a comparison, the semi-analytical relation derived by WRS is added.

The relation of WRS only satisfies the numerical calculations of single low-mass stars for core masses \( M_C > 0.22 \: M_\odot \). Therefore, the use of semi-analytical calculations, as those performed by WRS, is not justified if the initial core mass of the donor star is smaller than \( 0.22 \: M_\odot \). This lower limit on \( M_C \) corresponds with a lower limit on the initial and final orbital period of about 5 days (slightly depending on the mass of the donor star) and about 62 days (Eq. 1b), respectively.

Following WRS, the mass transfer rate is proportional to \( dR/dM_C \), which is the variation of the stellar radius \( R \) as a function of the core mass \( M_C \). For \( M_C < 0.22 \: M_\odot \) (i.e. \( P_i < 5 \: \text{d.} \)), \( dR/dM_C \), as derived from the single-star evolution calculations, is significantly lower than \( dR/dM_C \) as derived from the relation of WRS (see figure 3), which results in a
much lower mean mass transfer rate. The inclusion of magnetic braking in the numerical calculations does, however, increase the mass transfer rate again, resulting in the picture presented in Fig. 2.

Figure 3: The relation between the stellar radius $R$ and the Helium core mass $M_\text{core}$ in 0.7 to 2.0 $M_\odot$ single (sub)giants. For comparison, the semi-analytical relation derived by WR S is added as a dash-crossed line. In view of the differences between the semi-analytical and numerical results, we indicate that the use of the relation of WRS for core masses < 0.22 $M_\odot$ is not justified.

There is evidence that a fraction of the neutron stars in LMXBs are formed by accretion induced collapse (AIC) of a massive WD (see e.g. van den Heuvel, 1984, 1987). If, at the onset of mass transfer, the compact component in the system is a massive white dwarf, the X-ray lifetimes can be significantly reduced, because as long as the accreting object is a white dwarf, the system is not seen as a bright X-ray source. The mass-losing component in such a system may have to transfer a significant amount of mass before the WD collapses to a NS, since the occurrence of nova-explosions may expel a large part of the accreted matter from the system (Starrfield et al., 1985). In this case, only the remnant mass of the hydrogen envelope of the donor star at the moment of the AIC determines the lifetime of the newly formed LMXB. As a tool for the determination of the X-ray lifetime in case such a situation occurs, we present Fig. 4. It gives the lifetimes of LMXBs as a function of their final orbital period, for a certain amount of mass still to be transferred. It can easily be seen that, depending on the amount of mass to be transferred, the lifetimes of LMXBs can vary significantly. KN estimate that, on the average, the X-ray lifetime lasts only a third of the total possible accretion time (i.e. corresponding with the transfer of 0.2 $M_\odot$ towards the NS).
3.2 The results: the birth rate of LMXBs.

Using Eq. (1a), assuming that the total number of wide LMXBs ($P_{\text{orb}} > 0.67$ d) is $N_X = 33$ (Bradt and McClintock, 1983) and adopting an initial period ($P_i$) distribution of $n(P_i)dP_i = P_i^{-1}dP_i$, KN find an inverse birth rate for the LMXBs of $BR^{-1} = 8.5 \times 10^7$ yr for the rapid systems ($0.5 < P_i < 3.0$ days) and $BR^{-1} = 7.0 \times 10^5$ yr for the systems with initial periods within the total period range 0.5 and 300 days.

Using the results from PS (cf. Eq. 1d), adopting $\Delta M = 0.2 M_\odot$, as the total amount of mass accreted by the neutron star (KN) and averaging over the same ensemble of initial periods as used by KN, we find that the mean birth-rate $BR$ for the rapid LMXBs is given by:

$$BR = N \int f_r <P_i^{3.80}> / (2.3 \times 10^8) \text{ (yr}^{-1})$$

where $N$ is the number of progenitor systems of LMBRs with $P_{\text{orb}} > 0.67$ d, $f_r$ the fraction of rapid systems with $0.67 < P_i < 1.91$ days and the factor between brackets, i.e. $<P_i^{3.80}>$, represents the mean value over the total initial period distribution of $P_i^{3.80}$.

In their estimate of the total birth rate of LMXBs, KN considered the initial period range 0.5 d to 300 d, thereby including ASRs, i.e. systems with $P_i > 25$ d. However, this is inconsistent with the use of $N_X = 33$, since this number is determined by systems which must have had $P_i < 25$ d. Based on the initial period distribution, we find that the
fraction of systems with \( P_i > 25 \text{ d} \), with respect to the total initial period range 0.67 to 300 d, is 0.39. Hence, there must be about 22 ASRs and the total number \( N \) of progenitor systems of galactic LMBRPs is 55.

We adopt the same period distribution of KN and find that \( BR^{-1} = 7.7 \times 10^6 \text{ yr} \) for LMXBs with \( P_i < 1.91 \text{ days} \), a factor of 6 lower than derived by KN, for the same period range. We may expect that for the initial period range immediately following \( P_i = 1.91 \text{ days} \), the mean mass transfer rate is still higher, by a factor of at least 3, than the mass transfer rate derived from WRS (see figure 2). As a result, the mean lifetime of a LMXB with initial period longer than 1.91 days (or ASRs, if \( P_i > 25 \text{ d} \)) will be shorter. We expect that for

\[ 0.67 < P_i < 3.00 \text{ d}, \]

the inverse birth rate of the progenitor systems of rapid LMBRPs, \( BR^{-1} < 6.2 \times 10^6 \text{ yr} \) and that for the whole period range, it will be significantly lower than derived by KN. We find that the inverse birth rate for all systems with \( P_i > 0.67 \) is probably smaller than \( 1.4 \times 10^5 \text{ yr} \).

4. Discussion and conclusions.

Adopting an incidence of systems like PSR 1855+09 of 0.1 with respect to the population of single pulsars, we derive an inverse birth rate for the total sample of low mass radio binary pulsars of \( BR^{-1} = 7.1 \times 10^4 \text{ yr} \), and for rapid systems of \( 1.6 \times 10^5 \text{ yr} \). For the progenitor systems of LMBRPs, we find \( BR^{-1} < 1.4 \times 10^5 \text{ yr} \), for

\[ 0.5 < P_i < 300 \text{ days} \]

and \( BR^{-1} = 6.2 \times 10^6 \text{ yr} \), for \( P_i < 3.00 \text{ days} \). Thus, for the total range of periods the birth rates differ by less than a factor 2, whereas for the rapid systems there is a discrepancy of a factor of 39. We recall that KN found a discrepancy between the birth rates of short orbital period systems between 300 and 2000.

In view of the recent discovery of the binary 1.6 ms pulsar (Fruchter et al., 1988), Klužniak et al. (1988) Phinney et al., 1988, and van den Heuvel and van Paradijs (1988) suggest that rapidly spinning neutron stars in rapid LMBRPs may evaporate their secondaries. After at least a few times \( 10^{-2} M_\odot \) have been transferred, the NS may be spinning with a period in the millisecond range if the NS magnetic field strength is low (a few \( 10^8 \text{ G} \)). If mass transfer is then temporarily interrupted, for example by a random fluctuation in the stellar radius of the mass-
losing component, by only a few atmospheric scale-heights, the pulsar becomes active as a radio pulsar and may emit sufficient energy to "evaporate" the entire H-rich envelope of the giant, thereby greatly reducing the X-ray lifetime and simultaneously increasing the radio lifetime of the system. The fraction of mass effectively transferred determines the X-ray lifetime of the system. This effect will bring the birth-rates of rapid LMXBs and LMBRPs in still closer agreement.

Also the estimate of the total amount of galactic LMXBs may be uncertain and awaits confirmation. According to Blair et al. (1988), the total amount of these systems could possibly be a factor 5 higher than derived by Bradt and McClintock (1983), thereby decreasing the difference in birth-rates between both types of system with the same factor.

In conclusion, we find that the birth rates for the total sample of LMBRPs and their possible progenitors (i.e. wide LMXBs and ASRs) are reasonably in agreement. The discrepancy of at most a factor 39, between the birth-rate of the rapid LMBRPs and LMXBs, may be resolved by the destruction of potential LMXBs with relatively short orbital period by the process of evaporation.

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