The Orbital Period Distribution of Wide Binary Millisecond Pulsars

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Abstract.   We present results of a binary population synthesis study on the orbital period distribution of wide binary millisecond pulsars forming through four evolutionary channels. In three of the channels, the progenitor of the millisecond pulsar undergoes a common envelope phase prior to the supernova explosion which gives birth to the neutron star. In the fourth channel, the primary avoids the common-envelope phase and forms a neutron star when it ascends the asymptotic giant branch. The four formation channels yield an orbital period distribution which typically shows a short-period peak below 10 days, a long-period peak around 100 days, and a cut-off near 200 days. The agreement with the orbital period distribution of observed binary millisecond pulsars in the Galactic disk is best when the common-envelope ejection is efficient, the mass-transfer phase responsible for spinning up the pulsar is highly non-conservative, and no or moderate supernova kicks are imparted to neutron stars at birth.

1.   Introduction

In close binaries containing a neutron star (NS) and a non-compact star, the evolution of the latter and/or the orbit may drive the system into a semi-detached state where the non-compact star transfers mass to the NS. If the NS is able to accrete some of the transferred mass, the associated transfer of angular momentum will spin the NS up until a millisecond pulsar is born. At the end of the mass-transfer phase, the donor star's core is exposed as a white dwarf (WD) and the binary appears as a binary millisecond pulsar (BMSP). If the mass-transfer phase takes place when the donor is on the giant branch, the relation between the core mass and radius of the donor star, and the relation between the Roche-lobe radius and the orbital separation, lead to a correlation between the orbital period of the BMSP and the WD mass (e.g., Joss, Rappaport & Lewis 1987).

In this paper, we compare the orbital period distribution of simulated wide BMSPs from the BiSEPS (*Bi*nary *S*tellar *E*volution and *P*opulation *S*ynthesis) code with the orbital period distribution of BMSPs observed in the Galactic disk. In particular, we investigate whether a set of binary evolution parameters can

be found which is able to reproduce the observed distribution without including observational selection effects or detailed pulsar physics.

2. Binary Population Synthesis

We consider the evolution of a set of ZAMS binaries with initial component masses between $0.1\,M_\odot$ and $60\,M_\odot$, and initial orbital periods ranging from 10 to 10 000 days, up to a maximum evolutionary age of 15 Gyr. The initial primary masses are assumed to be distributed according to a Salpeter type initial mass function $\propto M_1^{-2.7}$ for $M_1 \geq 0.75\,M_\odot$, the initial mass ratio distribution is assumed to be flat, and the initial orbital separation distribution is assumed to be logarithmically flat.

A full description of the BiSEPS binary population synthesis code can be found in Willems & Kolb (2002). We here therefore only briefly recall the treatment of a few key processes in the formation of wide BMSPS:

- Common-envelope (CE) phases are treated in the usual way by equating the binding energy of the envelope to the orbital energy released by the in-spiraling component stars. The outcome of the phase depends on the envelope-ejection efficiency α_{CE} in the sense that larger values of α_{CE} yield larger post-CE orbital separations. In our standard model, we set $\alpha_{CE} = 1.0$.

- Asymmetric supernova (SN) explosions are assumed to impart a kick velocity to the newborn NS's center-of-mass. The direction of the kick velocity is assumed to be distributed isotropically in space, while the magnitude is drawn from a Maxwellian distribution with a velocity dispersion of 190 km/s. The post-SN orbital parameters of the binaries surviving the SN explosion are determined as in Kalogera (1996).

- NSs are thought to have a low accretion efficiency; this is mimicked by imposing an upper limit $(\Delta M_{NS})_{max} = 0.2\,M_\odot$ on the mass that can be accreted by a NS. As long as this upper limit is not reached, we adopt an average mass-accretion rate given by $\dot{M}_{NS} = (\Delta M_{NS})_{max}|\dot{M}_d|/M_d$, where M_d is the mass of the donor star. In addition, the NS accretion rate is limited to the Eddington rate at all times.

3. Evolutionary Channels

We consider four evolutionary channels leading to the formation of wide BMSPs (for a review see, e.g., Bhattacharya & van den Heuvel 1991). The majority of the systems is found to descend from binaries in which the primary (the initially most massive star) undergoes a CE phase prior to the formation of the NS. If the post-SN binary undergoes a stable mass-transfer phase from a low-mass giant (channel "He N") or a thermal-timescale mass-transfer phase from an intermediate mass star followed by a stable mass-transfer phase from a low-mass star (channel "He T"), the system evolves into a BMSP containing
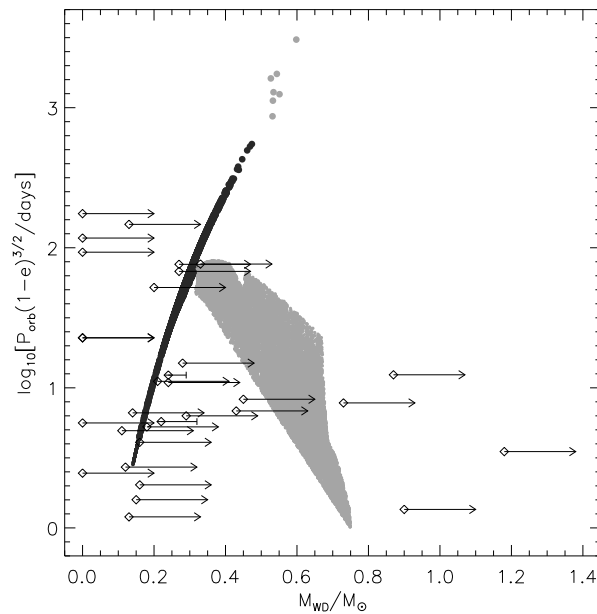
Figure 1.   Orbital periods vs. WD masses of wide BMSPs. Dark and light dots correspond to simulated BMSPs containing He and C/O WDs, respectively. Diamonds and arrows represent the observed Galactic BMSPs with the associated error bars.

a He WD. If, on the other hand, the binary undergoes a thermal-timescale mass-transfer phase from an intermediate mass star which is not followed by a stable mass-transfer phase, the system evolves into a BMSP containing a C/O WD (channel "CO T"). In the fourth formation channel, the BMSPs descend from binaries which do not form a CE prior to the formation of the NS. These systems rely on suitably directed kicks at the birth of the NS to decrease the orbital separation sufficiently for the low-mass companion to fill its Roche lobe on the AGB (see also Kalogera 1998). The outcome is a wide BMSP containing a C/O WD (channel "CO N"). The orbital periods and WD masses of wide BMSPs evolving through the four formation channels are shown in Figure 1.

4.   Orbital Period Distributions

The observed and simulated orbital period distributions of Galactic BMSPs are shown in Figure 2. The observed distribution is characterised by a short- and long-period peak around 10 and 100 days, respectively, a gap between 30 and 60 days, and a cut-off around 200 days. The simulated orbital period distributions are generally dominated by systems forming through the CO T channel. However, it is uncertain whether the accretion process during the thermal time scale mass-transfer phase giving rise to these systems is efficient enough to spin the NS up to a MSP. The systems forming through the CO N channel, on the other hand, provide the smallest contribution to the population of wide BMSPs and
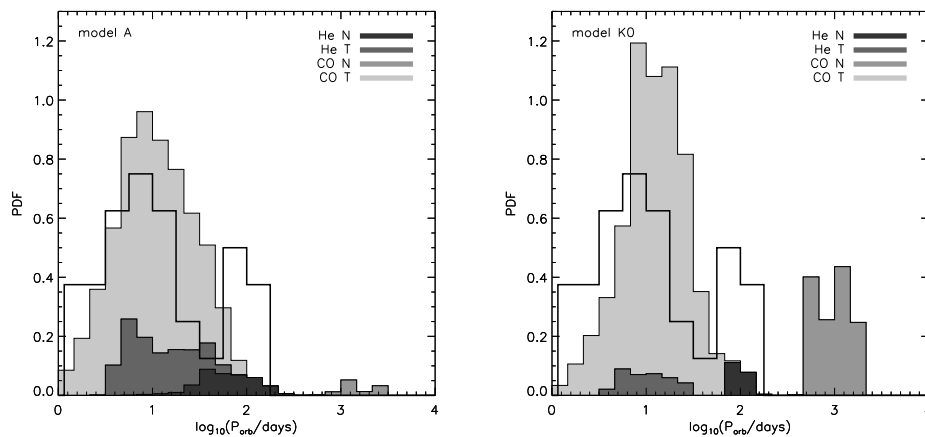
Figure 2.   Orbital period distribution of observed (solid line) and simulated (gray histograms) wide BMSPs. For clarity, the distribution functions of BMSPs forming through channels He N and CO N are multiplied by factors of 5 and 100, respectively. Left panel: standard set of parameters; right panel: no kicks imparted to NSs at birth.

have periods that are significantly beyond the 200-day cut-off period in the observed orbital period distribution. For the remainder of the paper, we therefore focus on the BMSPs forming through the He N and He T channels.

The orbital period distribution of BMSPs forming through channels He N and He T show a peak at long and short orbital periods, respectively. We tentatively identify these two subpopulations of BMSPs with the systems comprising the long- and short-period peak in the observed orbital period distribution. The long-period cut-off around 200 days is found irrespective of the accretion efficiency of NSs and results from the upper limit on the initial orbital periods beyond which the binary avoids the CE phase prior to the supernova explosion of the primary. Consequently, the cut-off period tends to increase with increasing values of α_{CE}. The short-period peak, on the other hand, is fairly insensitive to the values of α_{CE} and $(\Delta M_{NS})_{max}$. The kick-velocity dispersion, finally, determines the spread in the orbital periods after the SN explosion of the primary. In particular, small velocity dispersion yield narrow distributions of post-SN orbital periods, while large velocity dispersions yield wide distributions with relatively more systems at short orbital periods (see Fig. 7 in Kalogera 1996). These tendencies are clearly visible when comparing the orbital period distribution of our standard model with the orbital period distribution of a model where no kicks are imparted to NSs at birth (see the left- and right-hand panels of Fig. 2, respectively).

For conclusion, the observed orbital period distribution is best reproduced by simulations involving highly non-conservative mass transfer, common-envelope efficiencies equal to or larger than unity, and no or moderate supernova kicks at the birth of the NS. Even though the general effects of varying the population synthesis model assumptions are fairly clear, there are still too many uncertainties to come up with a unique set of model parameters giving the best possible
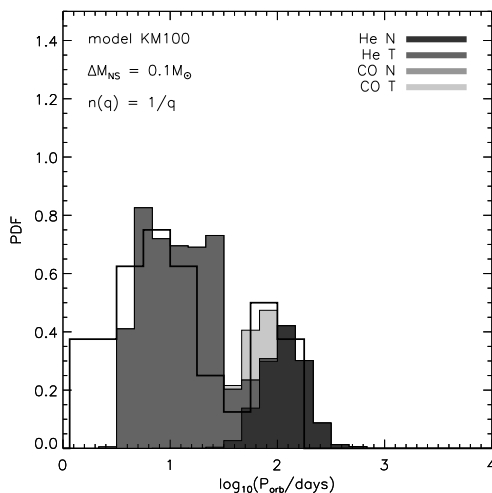
Figure 3. Example of a "best-fit" simulated orbital period distribution of Galactic wide BMSPs (gray histograms).

representation of the observed wide BMSP orbital period distribution (see also Pfahl et al. 2003). As an example of a "best-fit" solution, we show the orbital period distribution resulting from a simulation in which we adopted a Maxwellian kick-velocity distribution with a velocity dispersion of $100\,\mathrm{km/s}$, a common-envelope ejection efficiency equal to 1, and an upper limit on the mass that can be accreted by a NS of $0.2\,M_\odot$. In addition, we imposed a lower limit of $0.1\,M_\odot$ on the mass that needs to be accreted to spin the NS up to millisecond periods. This condition reduces the otherwise dominant channel CO T. The initial mass ratio distribution, finally, was taken to be $\propto 1/q$, which boosts the relative number of systems forming via mass transfer from low-mass giant stars (the He N channel). The model reproduces the observed short- and long-period peaks as well as the observed period gap, but it fails to produce BMSPs with orbital periods of 1–3 days. This potential problem may be resolved if the orbital angular momentum carried away by mass leaving the system during non-conservative mass transfer is assumed to come from the donor star instead of the accretor (Nelson, in this volume), or if the formation of BMSPs via accretion induced collapse is properly taken into account (Belczynski & Taam, in preparation). Our "best-fit" model also yields no systems containing C/O white dwarfs at orbital periods shorter than ~ 30 days, which may pose a problem to explain some of the observed systems with massive white dwarfs and orbital periods shorter than 20 days (cf. Fig. 1). This potential problem may be resolved by improved modelling of thermal-timescale mass-transfer phases involving Hertzsprung-gap donor stars.

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