Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
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Formation of Binary and Millisecond Pulsars: Puzzles and Possible Solutions

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Abstract. We present a systematic study of the evolution of intermediate- and low-mass X-ray binaries. Our calculations suggest that millisecond binary pulsars in wide orbits might have neutron stars born massive, or been formed through mass transfer driven by planet/brown dwarf-involved common envelope evolution.

Keywords. stars: millisecond pulsars, stars: evolution, MSPs: general

1. Introduction

Millisecond pulsars (MSPs) are old neutron stars (NSs) recycled during the previous intermediate/low-mass X-ray binary (I/LMXB) evolution (see Bhattacharya & van den Heuvel 1991 for a review). In the previous studies on I/LMXB evolution, a canonical NS (of mass $\sim 1.3 - 1.4\,M_{\odot}$) was usually adopted. In this work we perform calculations of I/LMXB evolution and discuss the properties of binary and millisecond pulsars (BMSPs), taking into account different initial NS masses (Shao & Li 2012).

2. Results of I/LMXB Evolution Calculations

Figure 1 shows the fate of the I/LMXB evolution in the initial $M_2 - P_{\rm orb}$ diagram. The left and right panels correspond to $1.0\,M_{\odot}$ and $1.8\,M_{\odot}$ NS, respectively. It is seen that the allowed space for successful evolution into binary pulsars (i.e., without common envelope evolution) is larger for $M_1 = 1.8\,M_{\odot}$ than for $M_1 = 1.0\,M_{\odot}$, since the lower mass ratio in the former case can stabilize mass transfer during the IMXB evolution.

Figure 2 shows the calculated correlation between the final orbital period $P_{\rm orb}^{final}$ and the mass of the white dwarf (WD) (the remnant of the donor) $M_{\rm WD}$. Low-mass donor stars may evolve to be either He WDs or CO WDs. Intermediate-mass donors can avoid He flash due to their higher temperature, forming CO WDs. Their $P_{\rm orb}^{final} - M_{\rm WD}$ distribution deviates from that of the low-mass branch obviously.

3. Comparison with BMSPs

In wide LMXBs, a specific correlation between the orbital period $P_{\rm orb}$ and the WD mass $M_{\rm WD}$ is obtained (Rappaport *et al.* 1995). Comparison with the observations shows that a significant population of BMSPs with He WD companion is generally consistent with this $P_{\rm orb} - M_{\rm WD}$ relation. However, there seems to be a systematic deviation from the correlation for pulsars with $P_{\rm orb} \gtrsim 60$ d, which seem to have WD companions lighter than expected (Tauris 1996).

Both systematic small values of the orbital inclination and large NS mass can increase $M_{\rm WD}$ for the given observed mass functions. Since there does not seem to be any observational selection effect favoring small inclination angle (Tauris 1996), we examine whether

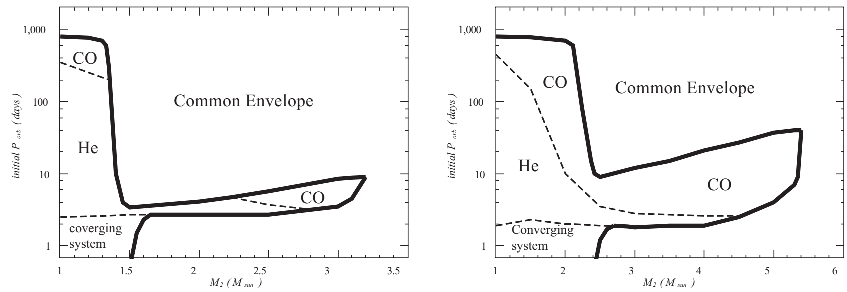

Figure 1. The allowed parameter space in the initial orbital period vs. donor mass plane for I/LMXBs to successfully form binary pulsars with He and CO WD companions.

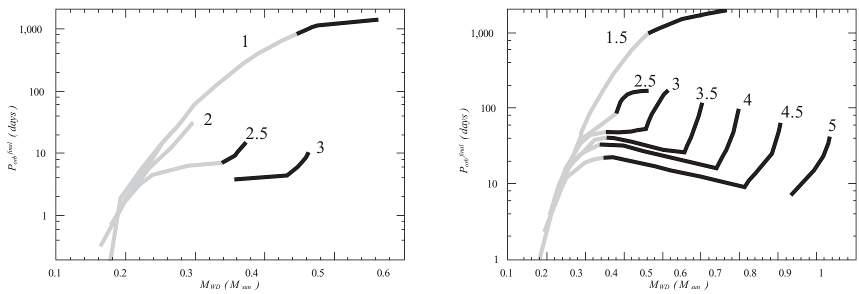

Figure 2. The final orbital period $P_{\rm orb}$ as a function of the WD mass $M_{\rm WD}$.

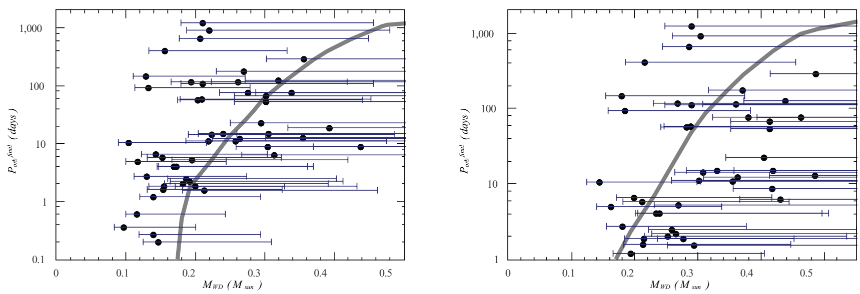

Figure 3. The orbital period as a function of the WD mass for MSPs with possible He WD companions.

the $P_{\rm orb} - M_{\rm WD}$ correlation can be accounted for if the long-period BMSPs have CO WD companions. In Fig. 3 we compare the relations between $P_{\rm orb}$ and $M_{\rm WD}$ in the cases that the NS has an initial mass of 1.0 $M_\odot$ (left panel) and 1.8 $M_\odot$ (right panel). Also plotted are binary pulsars with measured $P_{\rm orb}$ and $M_{\rm WD}$ (90% probability mass range for randomly oriented orbits) for a fixed NS mass of 1.2 and 2.0 $M_\odot$, respectively. It is seen that some binary pulsars with $P_{\rm orb} > 100$ d can fairly match the relation if they have massive NSs ($\sim 2M_\odot$) and heavy CO WDs (although in some cases small orbital inclination angles may be required), while for those with $P_{\rm orb} < 20$ d, statistically lighter NSs ($\sim 1.2M_\odot$) seem to follow the relation better.

In Fig. 4 we show the mass transfer rate $\dot{M}_2$, and the accreted mass ΔM_1 of the NS as a function of the final orbital period $P_{\rm orb}$. It shows that in general $\dot{M}_2 \gtrsim 0.1\dot{M}_{\rm Edd}$, and $\Delta M_1 \lesssim 0.3M_\odot$. We find that systems with initially massive NSs ($1.8\,M_\odot$) may accrete enough mass to evolve into BMSPs with 60 d $\lesssim P_{\rm orb} \lesssim 200$ d, , while light NSs in wide binaries are more likely to be partially recycled.

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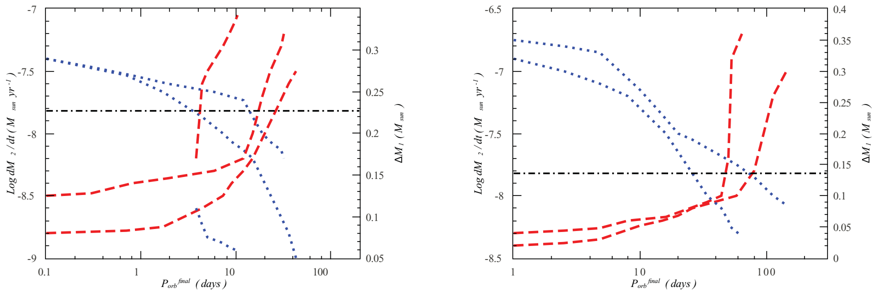

Figure 4. The mass transferred rate (red dashed curves) and accreted masses (blue dotted curves) of the NS as a function of the final orbital period.

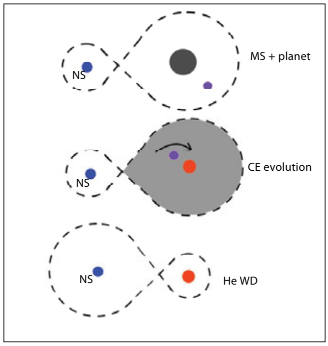

Figure 5. The schematic plot showing the possible formation process of wide BMSPs with a He WD companion.

For MSPs with low-mass He WD companions the above model obviously does not work. Here we suggest another possible solution. It is noted that solar-type stars are usually found to be surrounded by sub-stellar companions (usually planets and/or brown dwarfs). One may expect that in some wide LMXBs the companion star had possessed substellar companion(s) in close orbits like "hot Jupiters". When the star evolved on the giant branch it would become big enough to capture its planet/brown dwarf. The planet/brown dwarf spiraled into the envelope of the giant to initiate a CE phase. If there was enough orbital energy, the spiral-in process would expel the envelope of the giant, leaving a WD remnant. If the initial separation between the star and the substellar object(s) is less than tens of Solar radii, the final outcome would be an under-massive WD. A schematic view of the formation of BMSPs with planet/brown dwarf-involved CE evolution is shown in Fig. 5.

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