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Tauris, Th.M.; van den Heuvel, E.P.J.; Savonije, G.J.

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FORMATION OF MILLISECOND PULSARS WITH HEAVY WHITE DWARF COMPANIONS: EXTREME MASS TRANSFER ON SUBTHERMAL TIMESCALES

Thomas M. Tauris, Edward P. J. van den Heuvel, and Gerrit J. Savonije
Center for High-Energy Astrophysics and Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403,
NL-1098 SJ Amsterdam, The Netherlands; tauris@astro.uva.nl, edvdh@astro.uva.nl, gertjan@astro.uva.nl
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ABSTRACT

We have performed detailed numerical calculations of the nonconservative evolution of close X-ray binary systems with intermediate-mass (2.0–6.0 $M_\odot$) donor stars and a 1.3 $M_\odot$ accreting neutron star. We calculated the thermal response of the donor star to mass loss in order to determine its stability and follow the evolution of the mass transfer. Under the assumption of the "isotropic reemission model," we demonstrate that in many cases it is possible for the binary to prevent a spiral-in and survive a highly super-Eddington mass transfer phase ($1 \ll \dot{M}/\dot{M}_{\rm Edd} < 10^5$) on a subthermal timescale if the convective envelope of the donor star is not too deep. These systems thus provide a new formation channel for binary millisecond pulsars with heavy CO white dwarfs and relatively short orbital periods (3–50 days). However, we conclude that to produce a binary pulsar with a O-Ne-Mg white dwarf or $P_{\rm orb} \sim 1$ day (e.g., PSR B0655+64) the above scenario does not work, and a spiral-in phase is still considered the most plausible scenario for the formation of such a system.

Subject headings: binaries: close — stars: evolution — stars: mass loss — stars: neutron — white dwarfs

1. INTRODUCTION

Recently a large number of binary millisecond pulsars (BMSPs) with relatively heavy white dwarf (WD) companions have been reported. These pulsars form a distinct class of BMSPs (see Table 1) that is characterized by relatively slow spin periods ($P_{\rm spin} \simeq 10$–200 ms) and high period derivatives: $10^{-20} < \dot{P}_{\rm spin} < 10^{-18}$. It has been suggested that such BMSPs evolved through a common envelope and spiral-in phase (e.g., van den Heuvel 1994). This gives a natural explanation for their close orbits and the presence of a relatively heavy CO/O-Ne-Mg WD, if the mass transfer was initiated while the donor star (the progenitor of the WD) ascended the asymptotic giant branch. However, it has been argued that a neutron star engulfed in a common envelope might experience hypercritical accretion and thereby collapse into a black hole (e.g., Chevalier 1993; Brown 1995). If this picture is correct, then these BMSPs cannot have formed in a common envelope and spiral-in phase.

Here we investigate an alternative scenario for producing the mildly recycled BMSPs with He or CO WDs in close orbits, in which a 2–6 $M_\odot$ donor star with a nonconvective (or partly convective) envelope transfers mass on a subthermal timescale and yet in a dynamically stable mode.

2. STABILITY CRITERIA AND MODE OF MASS TRANSFER

The stability and nature of the mass transfer is very important in binary stellar evolution. It depends on the response of the mass-losing donor star and of the Roche lobe (e.g., Paczyński 1976; Soberman, Phinney, & van den Heuvel 1997). The mass transfer is stable as long as the donor star's Roche lobe continues to enclose the star. Otherwise it is unstable and proceeds on the shortest unstable timescale.

As long as the mass of the donor M_2 is less than 1.8 $M_\odot$, the mass transfer will be dynamically stable for all initial orbital periods (e.g., Tauris & Savonije 1999). These low-mass X-ray binaries (LMXBs) are the progenitors of the BMSPs with a helium WD companion. The observational absence of X-ray binaries with Roche lobe–filling companions more massive than ~2 $M_\odot$ has been attributed to their inability to transfer mass in such a stable mode that the system becomes a persistent long-lived X-ray source (van den Heuvel 1975; Kalogera & Webbink 1996). Below we investigate for these systems how the stability of the Roche lobe overflow (RLO) depends on the evolutionary status of the donor (and hence the orbital period) at the onset of mass transfer.

2.1. *Numerical Computations*

We have calculated the evolution of a large number of X-ray binaries with a donor star of mass $2 \leq M_2/M_\odot < 6$ and a 1.3 $M_\odot$ accreting neutron star. Both the radius of the donor star as well as its Roche lobe are functions of time and mass (as a consequence of nuclear burning, magnetic braking, and other tidal spin-orbit couplings). We used an updated version of Eggleton's numerical computer code (Pols et al. 1998) to keep track of the stellar evolution and included a number of binary interactions to carefully follow the details of the mass transfer process. For all donor stars considered here, we assumed a chemical composition of $X = 0.70$ and $Z = 0.02$ and a mixing-length parameter of $\alpha = l/H_p = 2.0$. We refer to Tauris & Savonije (1999) for a detailed description of our computer code.

2.2. *Highly Super-Eddington Mass Transfer*

The maximum accretion rate onto a neutron star is given approximately by the Eddington limit for spherical accretion of hydrogen gas, $\dot{M}_{\rm Edd} = 1.5 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$. If the mass transfer rate from the donor star $\dot{M}_2$ is larger than this limit, radiation pressure from the accreted material will cause the infalling matter to be ejected from the system at a rate $|\dot{M}| = |\dot{M}_2| - \dot{M}_{\rm Edd} \simeq |\dot{M}_2|$ if $\dot{M}_2 \gg \dot{M}_{\rm Edd}$. In systems with very large mass transfer rates, matter piles up around the neutron star and presumably forms a growing, bloated cloud engulfing a large fraction of the accretion disk. A system will only avoid a spiral-in if it manages to evaporate the bulk of the transferred matter via the liberated accretion energy. This would require the radius of the accretion cloud $r_{\rm cl} > R_{\rm NS}|\dot{M}_2|/\dot{M}_{\rm Edd}$ in order for the liberated accretion energy to eject the transferred material

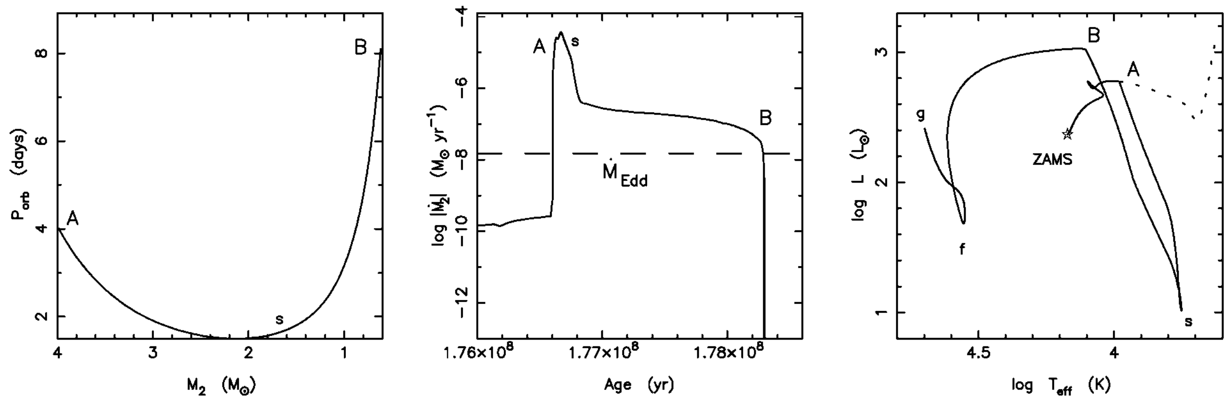

FIG. 1.—Evolution of an X-ray binary with $M_2 = 4.0\ M_\odot$ and $P_{orb} = 4.0$ days. *Left:* Evolution of P_{orb} as a function of M_2 (time is increasing to the right). *Middle:* Mass-loss rate of the donor as a function of its age since the ZAMS. *Right:* Evolution of the mass-losing donor (*solid line*) in an H-R diagram. The dotted line represents the evolutionary track of a single 4.0 $M_\odot$ star. The letters in the different panels correspond to one another at a given evolutionary epoch—see text for further explanation.

($\sim 0.1\dot{M}_{Edd}c^2 \gtrsim 1/2\dot{M}_2 v_{esc}^2$, where $v_{esc}^2 = 2GM_{NS}/r_{cl}$; R_{NS} is the radius of the neutron star). If the material which is to be ejected comes closer to the neutron star, it will have too much negative binding energy in order for the liberated accretion energy to expel it. At the same time, r_{cl} must be smaller than the Roche lobe radius of the neutron star during the entire evolution if formation of a common envelope (CE) is to be avoided.[1] A simple isotropic reemission model will approximately remain valid for our scenario. In this model it is assumed that matter flows over conservatively from the donor star to the vicinity of the neutron star before it is ejected with the specific orbital angular momentum of the neutron star. Assuming this to be the case we find that, even for extremely high mass transfer rates ($|\dot{M}_2| > 10^4\dot{M}_{Edd}$), the system can avoid a CE and spiral-in evolution.

3. RESULTS

3.1. *A Case Study:* $M_2 = 4.0\ M_\odot$ *and* $P_{orb} = 4.0$ days

In Figure 1 we show the evolution of a binary initially consisting of a neutron star and a zero-age main-sequence (ZAMS) companion star with masses $M_{NS} = 1.3\ M_\odot$ and $M_2 = 4.0\ M_\odot$, respectively, and initial orbital period $P_{orb} = 4.0$ days.

At the age of $t = 176.6$ Myr, the companion has evolved to fill its Roche lobe ($R_2 = 8.95\ R_\odot$; $T_{eff} = 9550$ K) and rapid mass transfer is initiated (*A*). The donor star has just evolved past the main-sequence hook in the H-R diagram and is burning hydrogen in a shell around a 0.56 $M_\odot$ helium core. Prior to the mass transfer phase, a radiation-driven wind ($|\dot{M}_2| \sim 4 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$) has caused the donor to decrease its mass slightly ($M_2 = 3.99\ M_\odot$) and consequently resulted in a slight widening of the orbit ($P_{orb} = 4.02$ days). Once the donor fills its Roche lobe, it is seen to lose mass at a very high rate of $|\dot{M}_2| \simeq 4 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1} = 2.7 \times 10^3\dot{M}_{Edd}$. At this stage the donor has only developed a very thin convective envelope of size $Z_{conv} = 0.015\ R_\odot$, so its envelope is still radiative and will therefore shrink in response to mass loss. At $t = 176.7$ Myr its radius has decreased to a minimum value of 3.38 $R_\odot$, but now $Z_{conv} = 0.97\ R_\odot$. At this point (*s*) the donor has a mass of 1.76 $M_\odot$, $T_{eff} = 5640$ K, and $P_{orb} = 1.59$ days. The donor expands again, but shortly thereafter its rate of expansion slows down, causing $|\dot{M}_2|$ to decrease to $\sim 10\dot{M}_{Edd}$.

The mass transfer ceases (*B*) when the donor has an age of 178.3 Myr. At this stage $P_{orb} = 8.11$ days, $R = 6.68\ R_\odot$, $Z_{conv} = 0.07\ R_\odot$, and $T_{eff} = 12{,}700$ K. The mass of the donor is 0.618 $M_\odot$. It still has a 0.56 $M_\odot$ helium core, but now only a 0.06 $M_\odot$ envelope consisting of 16% H and 82% He. The mass transfer phase (*A*–*B*) is relatively short ($t_X = 1.7$ Myr), and hence the neutron star will only accrete $\Delta M_{NS} = t_X\dot{M}_{Edd} = 0.03\ M_\odot$. This leads to relatively large values of P_{spin} and $\dot{P}_{spin}$ for the (mildly) recycled pulsar. Since the mass transfer rate is always highly super-Eddington during the RLO and the accreting neutron star will be enshrouded by a thick (bloated) disk, it is doubtful whether it will be observable as an X-ray binary during this phase—except very briefly just at the onset and near the end of the RLO.

We followed the evolution of the donor star further on. The donor continues to burn hydrogen in its light envelope. At $t = 186.4$ Myr (*f*), the helium burning is finally ignited ($L_{He}/L_H > 10$) in the core, which now has a mass of 0.596 $M_\odot$. After 70 Myr ($t = 253.8$ Myr since the ZAMS), the core-helium burning is exhausted (*g*). The 0.602 $M_\odot$ core then has a chem-

TABLE 1

OBSERVED PULSARS WITH A “HEAVY” WD COMPANION

PSR	P_{orb} (days)	f ($M_\odot$)	M_{WD}^{obs} ($M_\odot$)	P_{spin} (ms)	$\dot{P}_{spin}$
J1904+04[a]	15.75	0.0046	0.27	71.1	...
J1810−2005[a]	15.01	0.0085	0.34	32.8	1.3×10^{-19}
J1453−58[a]	12.42	0.13	1.07	45.3	...
J0621+1002	8.319	0.0271	0.540	28.9	$<8 \times 10^{-20}$
J1022+1001	7.805	0.0833	0.872	16.5	4.2×10^{-20}
J2145−0750	6.839	0.0242	0.515	16.1	2.9×10^{-20}
J1603−7202	6.309	0.00881	0.346	14.8	1.4×10^{-20}
J1157−5112[b]	3.507	0.2546	>1.20	43.6	$<9 \times 10^{-19}$
J1232−6501[a]	1.863	0.0014	0.175	88.3	1.0×10^{-18}
J1435−60[a]	1.355	0.14	1.10	9.35	...
B0655+64	1.029	0.0714	0.814	196	6.9×10^{-19}
J1756−5322[b]	0.453	0.0475	0.683	8.87	...

NOTE.—M_{WD}^{obs} is calculated assuming $M_{NS} = 1.4\ M_\odot$ and $i = 60°$.

[a] New pulsar, Parkes Multibeam Survey (Manchester et al. 2000).

[b] New pulsar (R. Edwards et al. 2000, in preparation).

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[1] Note that if no efficient cooling processes are present in the accretion disk, then the incoming matter retains its net (positive) energy and is easily ejected in the form of a wind from the disk (Narayan & Yi 1995; Blandford & Begelman 1999). Even if the arriving gas is able to cool, interactions between the released radiation from this process and the infalling gas may also help to eject the matter. In both cases r_{cl} can be smaller than estimated above.

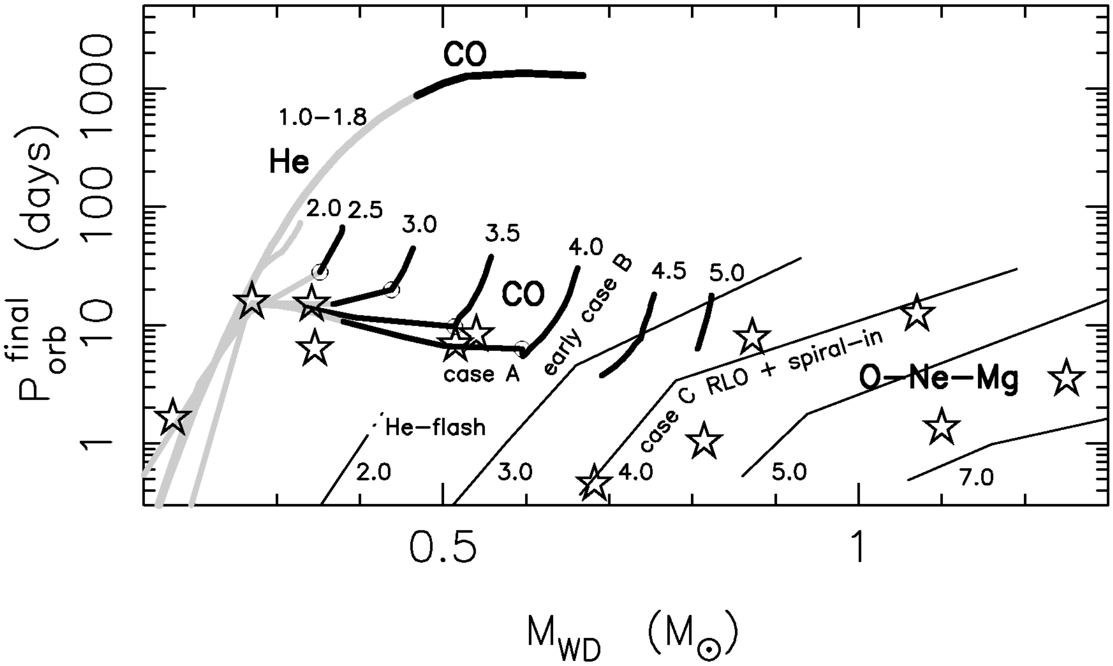

FIG. 2.—Final $P_{\rm orb}$ as a function of WD mass for different BMSPs. Next to each curve is given the initial mass of the donor star (the progenitor of the WD) used in our evolutionary calculations. The free parameter in each curve is the initial $P_{\rm orb}$ (at the onset of the RLO). The curves in gray color represent the formation of BMSPs with helium WDs, while the black curves are BMSPs with CO WDs. The open circles on some of the curves indicate the transition from case A to early case B RLO mass transfer (i.e., whether or not the donor burned hydrogen in the core at the onset of the RLO; Kippenhahn & Weigert 1990). The thin lines show the calculated parameters for systems which evolved through a CE and spiral-in phase scenario assuming an efficiency parameter of $\eta_{\rm CE}\lambda = 1.0$ (e.g., van den Heuvel 1994). The 12 observed BMSPs with a "heavy" WD companion are marked with a star; see Table 1.

ical composition of 19% C, 79% O, and 2% Ne. It is surrounded by a 0.016 $M_\odot$ envelope (16% H, 82% He, and 1% N_{14}). The central density is $\rho_c = 4.13 \times 10^4$ g cm^{-3}, and $R_2 = 0.21\ R_\odot$. From here on the star contracts and settles as a hot CO WD. We have now demonstrated a scenario for producing a BMSP with the same characteristics as those listed in Table 1.

3.2. *The $P_{\rm orb}$-$M_{\rm WD}$ Diagram*

In Figure 2 we have plotted the calculated final orbital periods as a function of the mass of the WD companion (the remnant of the donor) for a given initial mass of the donor star. The values for the BMSPs which originated from a binary with a low-mass companion (the former LMXBs with $M_2 \lesssim 1.8\ M_\odot$ located on the upper branch) are taken from Tauris & Savonije (1999). These WDs are expected to be helium WDs—unless the initial orbital period was very large ($P_{\rm orb} > 150$ days) so a relatively heavy helium core developed prior to the RLO, in which case the helium core later ignited, forming a CO WD. The final product of X-ray binaries with $M_2 > 2\ M_\odot$ is seen to deviate significantly from the low-mass branch. The reason is that the former systems had a large mass ratio, $q \equiv M_2/M_{\rm NS}$, which caused the binary separation to shrink initially upon mass transfer (see Fig. 1). Such systems only "survive" the mass transfer phase if the envelope of the donor is radiative or slightly convective. This sets an upper limit on the initial orbital period for a given system. If the donor is in a wide binary, it develops a deep convective envelope prior to filling its Roche lobe, and it will therefore expand rapidly in response to mass loss which, in combination with the orbital shrinking, will result in the formation of a CE and a (tidally unstable) spiral-in evolution.

In Figure 3 we show how the final orbital period and the mass of the WD depends on the initial orbital period for a binary with $M_2 = 4.0\ M_\odot$. We notice that the question of initiating RLO before or after the termination of hydrogen core burning (case A or early case B, respectively) is important for these relations. For initial $P_{\rm orb} < 2.4$ days (case A RLO), $P_{\rm orb}^f$ decreases with increasing $P_{\rm orb}$. The reason is simply that in these systems the donor star is still on the main-sequence and the mass of its helium core, at the onset of RLO, increases strongly with $P_{\rm orb}$, and therefore the amount of material to be transferred (the donor's envelope) decreases with $P_{\rm orb}$. Since the orbit widens efficiently near the end of the mass transfer, when the mass ratio between donor and accretor has been inverted (see Fig. 1), $P_{\rm orb}^f$ will also decrease as a function of initial $P_{\rm orb}$. However, for $P_{\rm orb} > 2.4$ days (early case B RLO), the final orbital period increases with initial orbital period as expected and the core mass of the donor only increases slightly (due to hydrogen shell burning) as a function of initial $P_{\rm orb}$.

3.3. *The Initial (M_2, $P_{\rm orb}$) Parameter Space*

In Figure 4 we outline the results of our work in a diagram showing the fate of a binary as a function of its initial $P_{\rm orb}$ and the value of M_2. We conclude that X-ray binaries with $2 \lesssim M_2/M_\odot < 6$ can avoid a spiral-in and CE evolution if $P_{\rm orb}$ is between 1 and 20 days, depending on M_2. If the initial $P_{\rm orb}$ is too short, the systems will obviously enter a CE phase, since these systems always decrease their orbital separation when the mass transfer is initiated.[2] On the other hand, if the initial $P_{\rm orb}$

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[2] In narrow binaries the amount of available orbital energy (a possible energy source for providing the outward ejection of the envelope) is small and hence the neutron star is most likely to spiral in toward the (unevolved) core of the donor, forming a Thorne-Zykow–like object. In that case the neutron star will probably undergo hypercritical accretion and collapse into a black hole.

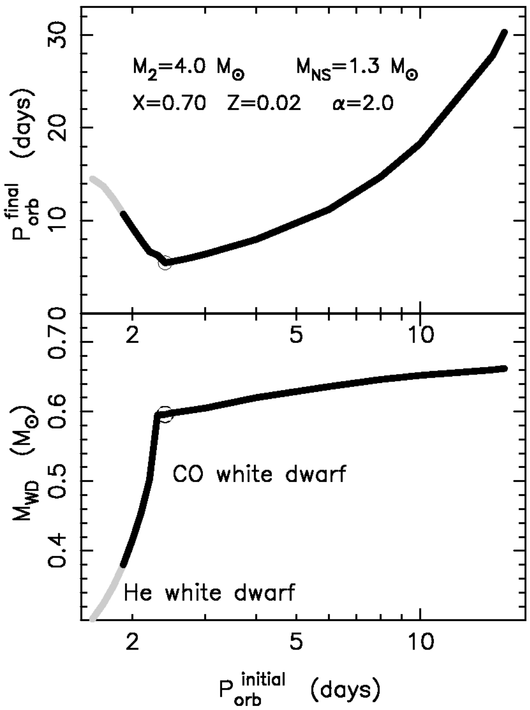

FIG. 3.—Dependence of final orbital period (*top*) and mass of the WD (*bottom*) on the initial orbital period $P_{\rm orb}$.

is too large the donor develops a deep convective envelope prior to RLO and a runaway mass transfer event is unavoidable, also leading to a CE formation. For systems with $M_2 \lesssim 1.8\ M_\odot$ and initial $P_{\rm orb} < 1$ day, the outcome is a BMSP with an ultra–low-mass degenerate hydrogen star (e.g., PSR J2051−0827; see Ergma, Sarna, & Antipova 1998).

4. DISCUSSION

We have now demonstrated how to form a BMSP with a relatively heavy (He or CO) WD companion without evolving through a CE phase. If a substantial fraction of BMSPs have evolved through a phase with super-Eddington mass transfer on a subthermal timescale (a few Myr), this will eliminate the need for a long X-ray phase. This would therefore help solving the birthrate problem between BMSPs and LMXBs (Kulkarni & Narayan 1988) for systems with $P^f_{\rm orb} < 50$ days.

It has recently been suggested (Podsiadlowski & Rappaport 2000; King & Ritter 1999) that Cygnus X-2 descended from an intermediate-mass X-ray binary via a scenario that resembles the one described here. We confirm that Cyg X-2 is a progenitor candidate for a BMSP with a heavy WD.

It is seen from Figure 2 that we cannot reproduce the systems with very massive O-Ne-Mg WDs or the short orbital periods (≲3 days) observed in some systems with a CO WD. We therefore conclude that these binaries most likely evolved through a CE phase in which frictional torques were responsible for their present short $P^f_{\rm orb}$ (see thin lines in Fig. 2 and light gray area in Fig. 4). These systems therefore seem to originate from binaries that initially had a relatively *large* $P_{\rm orb}$ and case C RLO—otherwise, if $P_{\rm orb}$ was smaller components would have coalesced either in the spiral-in process or as a result of gravitational wave radiation shortly thereafter (typically within 1 Gyr for systems surviving case B RLO and spiral-in).

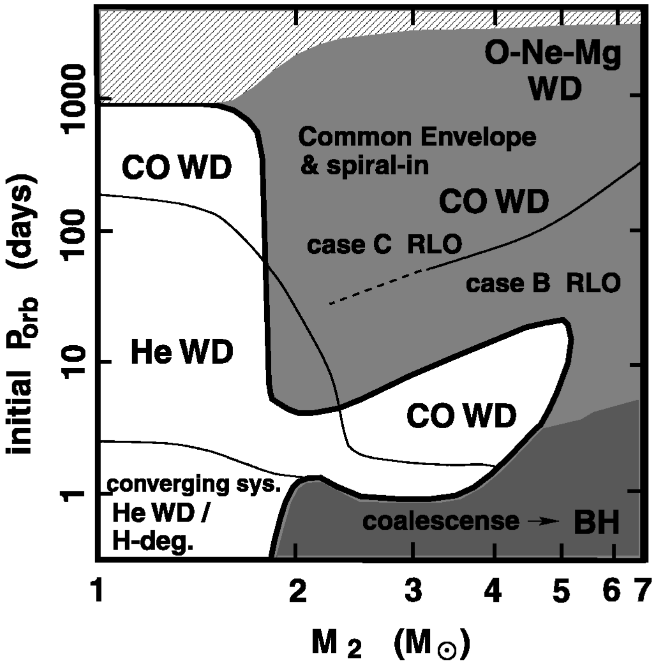

FIG. 4.—Allowed parameter space (*white area*) for producing BMSPs without evolving through a CE phase. If $M_2 > 1.8\ M_\odot$ and the donor has a deep convective envelope at the onset of mass transfer (i.e., $P_{\rm orb}$ is large), the system will evolve into a CE and spiral-in phase. This is also the case if the initial period is very short and $M_2 > 1.8\ M_\odot$. In the latter case the neutron star may collapse into a black hole.

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