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FORMATION OF THE GALACTIC MILLISECOND PULSAR TRIPLE SYSTEM PSR J0337+1715—A NEUTRON STAR WITH TWO ORBITING WHITE DWARFS

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ABSTRACT

The millisecond pulsar in a triple system (PSR J0337+1715, recently discovered by Ransom et al.) is an unusual neutron star with two orbiting white dwarfs. The existence of such a system in the Galactic field poses new challenges to stellar astrophysics for understanding evolution, interactions, and mass transfer in close multiple stellar systems. In addition, this system provides the first precise confirmation for a very wide-orbit system of the white dwarf mass–orbital period relation. Here, we present a self-consistent, semi-analytical solution to the formation of PSR J0337+1715. Our model constrains the peculiar velocity of the system to be less than 160 km s^{-1} and brings novel insight to, for example, common envelope evolution in a triple system, for which we find evidence for in-spiral of both outer stars. Finally, we briefly discuss our scenario in relation to alternative models.

Key words: binaries: close – pulsars: individual (PSR J0337+1715) – stars: mass-loss – stars: neutron – supernovae: general – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Stars are possibly always formed in multiple systems (e.g., Bonnell et al. 2003), and observational estimates suggest that about 20%–30% of all binary stars are in fact members of triple systems (Tokovinin et al. 2006; Rappaport et al. 2013). Triple systems can remain bound with a long-term stability if they have a hierarchical structure (e.g., a close inner binary with a third star in relatively distant orbit). In addition, a number of peculiar binary pulsars have recently been discovered, such as PSR J1903+0327 (Champion et al. 2008), which require a triple system origin (e.g., Freire et al. 2011; Portegies Zwart et al. 2011; Pijloo et al. 2012).

The discoveries of binaries with a triple origin is not unexpected. Iben & Tutukov (1999) estimated that in ∼70% of the triple systems, the inner binary is close enough that the most massive star will evolve to fill its Roche lobe. Furthermore, in ∼15% of the triples, the outer third (tertiary) star may also fill its Roche lobe at some point, possibly leading to disintegration or production of rare configurations with three degenerate objects in the same system. Recently, Ransom et al. (2014) have reported the discovery of PSR J0337+1715, which is the first example of such an exotic system—a neutron star (NS) orbited by two white dwarfs (WDs).

PSR J0337+1715 is a triple system located at a distance of ∼1.3 kpc. It contains a 1.438 $M_\odot$ radio millisecond pulsar (MSP) with a spin period of $P = 2.73$ ms and two WDs with masses of $M_{\rm WD,2} = 0.197\,M_\odot$ and $M_{\rm WD,3} = 0.410\,M_\odot$, and orbital periods of $P_{\rm orb,12} = 1.63$ days and $P_{\rm orb,3} = 327$ days, respectively. Thus, this triple system is highly hierarchical with a close inner binary and a distant tertiary star. In addition, the system is almost exactly coplanar ($\delta_i = 0\overset{\circ}{.}01$), and the orbits are quite circular with eccentricities of $e_{12} = 6.9 \times 10^{-4}$ and $e_3 = 0.035$ (Ransom et al. 2014).

Here, we investigate the formation of such a triple compact object system and present a model which aims to explain and reconcile the observed data with current theories of stellar interactions.

2. PROGENITOR EVOLUTION OF PSR J0337+1715

To investigate the formation of PSR J0337+1715 we start with constraints obtained from the present-day triple system and trace the evolution backward. Before elaborating on the details, we briefly summarize the outline of our model which is illustrated in Figure 1. Numerical parameters are provided in Table 1.

2.1. Summary of Our Model

According to our model, the system started out on the zero-age main sequence (ZAMS) with a roughly 10 $M_\odot$ primary star and two companions with masses of about 1.10 $M_\odot$ and 1.30 $M_\odot$, for the secondary and the tertiary star, respectively (Table 1, stage 1). After a common envelope (CE) phase (stage 2), where the extended envelope of the primary engulfed the other two stars (initially only embedding the secondary star; later also partly the tertiary star), the orbital period of the inner system was $P_{\rm orb,12} = 2.47$ days and the orbital period of the outer star was $P_{\rm orb,3} = 17.1$ days. Following a second mass transfer (Case BB, stage 3) and a supernova (SN) explosion (stage 4), they became $P_{\rm orb,12} = 1.55$ days and $P_{\rm orb,3} = 15.3$ days, which after orbital circularization (before stage 6), became $P_{\rm orb,12} = 1.55$ days and $P_{\rm orb,3} = 14.2$ days. The last set of values were the orbital periods at the onset of the first (outer) low-mass X-ray binary (LMXB) phase, which ended with $P_{\rm orb,12} = 1.50$ days and $P_{\rm orb,3} = 250$ days, before the second (inner) LMXB phase left the system with its present observed properties. We now describe in more detail the physical properties of our model.

2.2. The M_{WD}–P_{orb} Relation

A close triple system like PSR J0337+1715 with one NS and two WDs requires two LMXB phases. Although PSR J0337+1715 was substantially less hierarchical earlier in its evolution, the system seems to have evolved through both of its LMXB phases, in effect, mainly via binary interactions, with only small dynamical perturbations from the second or third

Table 1
Triple System Parameters at the Onset of Each Stage in Our Scenario (Figure 1) for the Formation of PSR J0337+1715

Parameter			Stage								
			1	2	3	4	5	6	7	8	9
Age of the system	t	(Myr)	0.0	23.3	23.3	25.1	25.2	5500	5517	8500	10,500
Mass of primary star	M_1	$(M_\odot)$	10.0	9.90	2.90	1.70	1.28	1.28	1.30	1.30	1.438
Mass of secondary star	M_2	$(M_\odot)$	1.10	1.10	1.10	1.10	1.10	1.10	1.12	1.12	0.197
Mass of tertiary star	M_3	$(M_\odot)$	1.30	1.30	1.30	1.30	1.30	1.30	0.410	0.410	0.410
Orbital period of inner binary	$P_{\rm orb,12}$	(days)	835	849	2.47	0.95	1.55	1.55	1.50	0.90	1.63
Orbital period of tertiary star	$P_{\rm orb,3}$	(days)	4020	4080	17.1	15.7	15.3	14.2	250	250	327
Eccentricity of inner binary	e_{12}		0.00	0.00	0.02	0.01	0.24	0.20	0.02	0.00	0.00
Eccentricity of outer orbit	e_3		0.00	0.00	0.04	0.04	0.22	0.03	0.03	0.03	0.03
Stability parameter	$(R_{\rm peri}/a_{\rm in})$		2.96	2.96	3.83	7.07	4.15	4.89	30.8	43.3	35.6
Critical stability limit	$(R_{\rm peri}/a_{\rm in})_{\rm crit}$		2.93	2.93	3.21	3.44	3.93	3.80	3.04	3.04	3.13
Temperature of outer WD	$T_{\rm eff,3}$	(K)							18,000	5800	4300

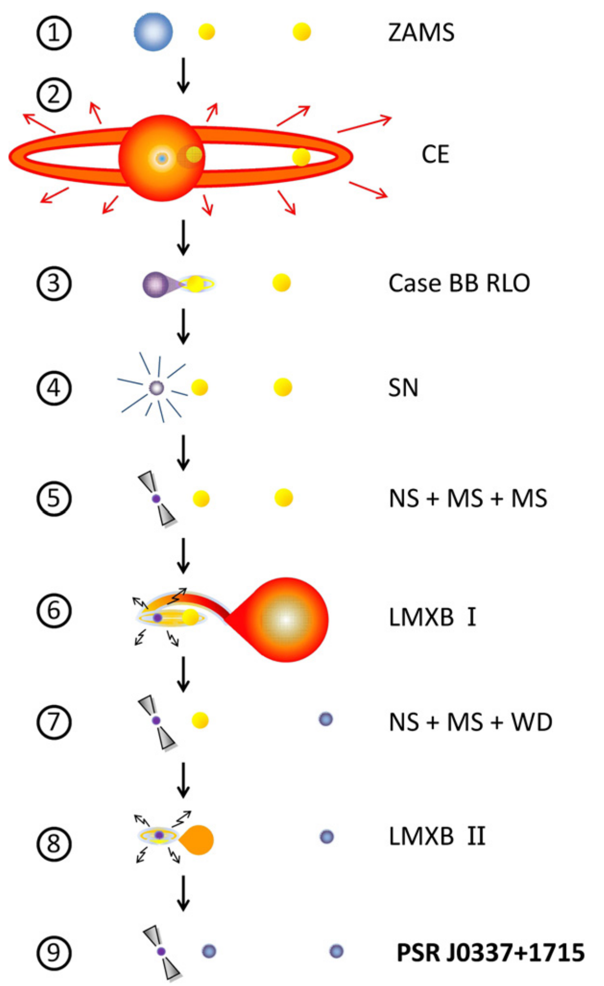

Figure 1. Illustration of our triple star evolution from the zero-age main sequence (ZAMS) to the present observed system PSR J0337+1715. Numerical parameters are given in Table 1. The initially massive B star evolves to initiate Roche-lobe overflow (RLO) toward the inner G/F star, leading to dynamical unstable mass transfer and the formation of a common envelope (CE), partially embedding the outer F star. The resulting helium star (the naked core of the massive star) expands and initiates another phase of (Case BB) RLO, before it collapses into a neutron star (NS) in a supernova (SN) explosion. Thereafter, the system becomes visible as a young radio pulsar with two main-sequence (MS) stars. Given that the tertiary star is more massive than the secondary star, the outer LMXB phase (lasting 15–20 Myr) occurs before the inner LMXB phase. The latter mass-transfer episode proceeds on a long timescale (2 Gyr), causing the NS to become a fully recycled MSP when finally orbited by two white dwarfs (WDs).

(A color version of this figure is available in the online journal.)

star. The important piece of evidence for this comes from the masses and orbital periods of the WDs which fall exactly as predicted by the $M_{\rm WD}$–$P_{\rm orb}$ relation for LMXB evolution (e.g., Savonije 1987; Rappaport et al. 1995; Tauris & Savonije 1999; van Kerkwijk et al. 2005). The match between this theoretical relation and the observational data for PSR J0337+1715 is excellent. This is demonstrated in Figure 2 where we plot all available data of helium WDs with masses measured to an accuracy $1\sigma < 0.1\ M_{\rm WD}$. These helium WDs are companions to pulsars or found in binaries with A-type main-sequence (MS) stars.

The eccentricities of both orbits are, although small, one to two orders of magnitude larger than expected theoretically for isolated binaries with similar components and orbital periods (Phinney & Kulkarni 1994). Although this may be a result of mutual triple interactions, a few binary pulsars with WD companions in the Galactic field have similar eccentricities (see Figure 4 in Tauris et al. 2012).

2.3. *Evolution of the Two LMXB Phases*

The two WDs orbiting PSR J0337+1715 are the remnants of two LMXB phases. Optical observations by Kaplan et al. (2014) show that the inner WD is quite hot (15,800 ± 100 K), whereas the outer WD is too cold to be detected. Therefore, we assume in the following that the inner WD formed last (see Section 3.3 for a discussion).

We can deduce that both LMXB phases evolved highly nonconservatively since the low MSP mass of 1.438 $M_\odot$ implies that it cannot have accreted much material (at most 0.1–0.2 $M_\odot$ in total; in our model we assume a NS birth mass of 1.28 $M_\odot$). Since the presently observed (post-LMXB) orbital period of the inner binary, $P_{\rm orb,12} = 1.63$ days is close to the so-called bifurcation period (between 1 and 2 days; Pylyser & Savonije 1989; Ma & Li 2009), below which magnetic braking is dominant in LMXBs (Rappaport et al. 1983) and above which the widening of the orbit is significant, we also conclude that the pre-LMXB (post-SN) orbital period of the inner binary must have been close to this value.

For the preceding outer LMXB phase, there is further evidence for highly nonconservative evolution since the mass-transfer rate must have been super-Eddington for such a wide system (initially $P_{\rm orb,3} = 14.2$ days) where the donor star had a deep convective envelope at the onset of the Roche-lobe overflow (RLO; Tauris & Savonije 1999; Podsiadlowski et al. 2002). During the rapid outer LMXB phase, we expect the pulsar only to be mildly recycled—possibly with a spin period between

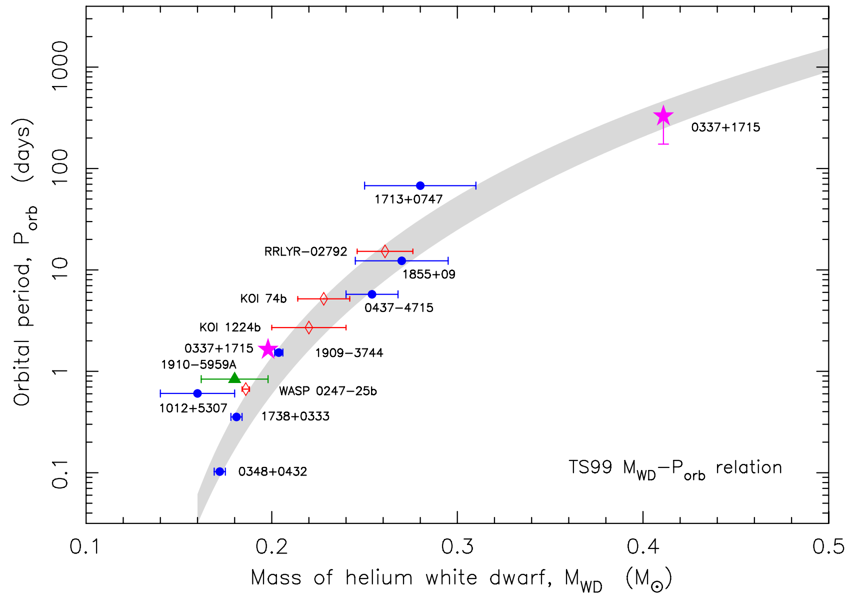

Figure 2. $M_{\rm WD}$–$P_{\rm orb}$ relation (TS99), as calculated by Tauris & Savonije (1999). The width of the relation is caused by using metallicities from $Z = 0.001$–0.02. Observational data is plotted for helium WD companions orbiting pulsars, for which the 1σ uncertainties are less than 10% of $M_{\rm WD}$. Also included are four Galactic field proto-WDs orbiting an A-type MS star (WASP 0247-25b, KOI 1214b, KOI 74b, and RRLYR−02792). The discovery of the triple MSP J0337+1715 adds two important high-precision data points to this graph and strengthens the validity of the relation. The error bar plotted for the outer WD is caused by an uncertainty in the widening of the outer orbit during the inner LMXB phase (see text). Theoretically, the relation becomes uncertain for $P_{\rm orb} < 1$ day. (For references to data, with increasing $P_{\rm orb}$, see Antoniadis et al. 2013, 2012; van Kerkwijk et al. 2005; Maxted et al. 2013; Corongiu et al. 2012; Jacoby et al. 2005; Ransom et al. 2014; Breton et al. 2012; van Kerkwijk et al. 2010; Verbiest et al. 2008; Splaver 2004; Pietrzyński et al. 2012; Splaver et al. 2005; Ransom et al. 2014).

(A color version of this figure is available in the online journal.)

25 ms and 1 s (a typical value for pulsars with a WD and $P_{\rm orb} > 200$ days; Tauris et al. 2012). Effective recycling of the MSP was obtained in the subsequent long-lasting inner LMXB phase.

The masses of the two WD progenitor stars are constrained, on the one hand, by requirements of the development of a degenerate helium core *and* dynamically stable mass transfer ($M_{2,3}^{\rm ZAMS} \leqslant 1.6\,M_\odot$) and, on the other hand, by nuclear evolution and WD cooling within a Hubble time ($M_{2,3}^{\rm ZAMS} > 1.0\,M_\odot$). The estimated component masses before/after the mass transfer then yield the amount of mass lost from the system.

The changes of the orbital separations as a result of LMXB mass transfer/loss can be found by solving the orbital angular momentum balance equation within the isotropic re-emission model (Soberman et al. 1997), but with some modification. For example, we cannot assume a pure fast (Jeans mode) wind mass loss from the inner binary with respect to the tertiary star during the inner LMXB phase (stage 8). Some of the inner binary material might be lost in a rather slow wind which only causes a moderate widening (if any) of $P_{\rm orb,3}$ during this phase. Nevertheless, following the outer LMXB phase (stage 6), $P_{\rm orb,3}$ could have been smaller than observed today (327 days). In the most extreme case, (Jeans mode) it could be as short as 175 days, given that the semimajor axis of the outer orbit in this case changes according to $a_{3f} = a_{3i}\,(M_i/M_f)$, where M is the total mass of the triple system and the indices i and f refer to initial and final values, respectively. Here we assume a more moderate value of 250 days.

The major uncertainties in our modeling are related to (1) spin–orbit couplings mediated by tidal torques (e.g., magnetic braking) and (2) accretion onto the inner binary system during mass transfer from the tertiary star (stage 6) and the poorly known specific orbital angular momentum of the ejected mass. Presumably, an inner circumbinary disk (Dermine et al. 2013) will be formed which may subsequently influence the evolution of the inner orbit. However, investigating the dynamical effects of the SN explosion helps to constrain the properties of the pre-LMXB systems.

2.4. The Dynamical Effects of the SN Explosion

A general discussion of dynamical effects of asymmetric SNe in hierarchical multiple star systems is found in Pijloo et al. (2012), and references therein. Here, we have simulated the dynamical effects of the SN explosion that created the NS in the PSR J0337+1715 system. In Figure 3, we have plotted the survival probability of our best model for the triple system as a function of the recoil velocity immediately imparted to the inner system (i.e., the "inner binary kick," w_{12}) as a consequence of the SN. All relevant pre-SN parameters are stated in the figure (see also Table 1, stage 4). Along the plotted curves are examples of average values of w_{12} for kick velocities between 0 and 550 km s^{-1} which were imparted to the newborn NS. For estimating the resulting values of w_{12}, we only considered systems which survived the SN in long-term stable orbits (Section 3.1), and for which the inner binary avoided merging.[4]

Given the constraints on the post-SN evolution to meet the requirements for PSR J0337+1715, we find that it may even have survived a NS kick up to 400 km s^{-1}. The resulting peculiar velocities of the triple system range between 15 and 160 km s^{-1}.

2.5. Pre-SN Core Mass and Case BB RLO

The triple system is much more likely to survive the explosion if the pre-collapsing core mass is low. A pre-SN core mass of

[4] The plotted probabilities do not take into account the specific requirements on the value of the post-SN $P_{\rm orb,3}$ necessary for forming PSR J0337+1715. If including this specific constraint, the probabilities shown would be much lower.

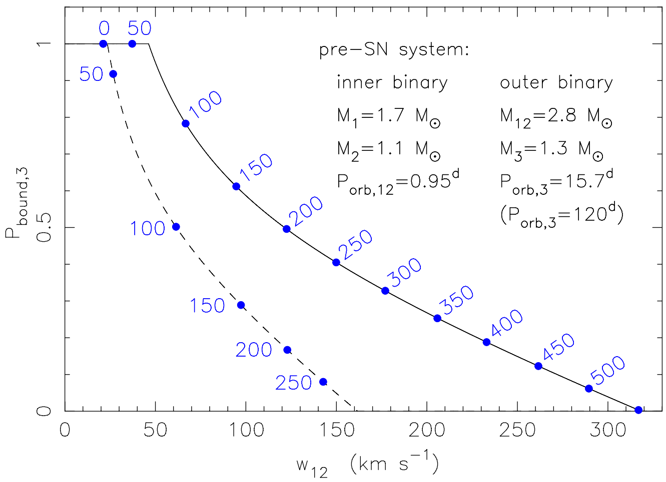

Figure 3. Probability for a triple system to survive a given recoil velocity, w_{12}, obtained by the inner binary due to a SN. The bullet points represent average values of w_{12} for the stated kick magnitudes (in km s^{-1}) imparted on a newborn 1.28 $M_{\odot}$ NS in the inner binary. The kick directions were chosen from an isotropic distribution and simulations were done for random orbital phases between the mutual orbits. The solid (dashed) line is for a pre-SN $P_{\rm orb,3}$ = 15.7 days ($P_{\rm orb,3}$ = 120 days). When calculating $\langle w_{12} \rangle$ only triple systems surviving the SN in long-term dynamically stable orbits, and for which the inner binary avoided merging, were considered. The assumed pre-SN core mass is $M_1 = 1.7\,M_{\odot}$. All other relevant pre-SN triple parameters are given in the figure.

(A color version of this figure is available in the online journal.)

only $\sim$1.7 $M_{\odot}$ is indeed expected if the progenitor star (say, $M_1 = 10\,M_{\odot}$) lost its hydrogen-rich envelope on the red giant branch (RGB), because the resulting naked helium core itself ($\sim$2.9 $M_{\odot}$) would expand and give rise to Case BB RLO (Habets 1986), leaving an even further stripped pre-SN core during stage 3. In case the NS progenitor did not lose its envelope until the asymptotic giant branch, the collapsing core mass could have been much larger. However, we find that a collapsing core mass of, for example, 3.2 $M_{\odot}$ decreases the survival probability considerably and leaves the triple system with $v \sim 150$ km s^{-1}.

2.6. *The Common Envelope Evolution—New Lessons from a Triple System*

The outcome of the CE evolution is crucial for determining the pre-SN core mass and orbital periods (e.g., Tauris & Dewi 2001), and thus for the survival probability of the triple system. Unfortunately, CE evolution is the least understood of the important interactions in close binary systems (see Ivanova et al. 2013, for a recent review). For close triple systems, understanding the CE evolution is an even more complicated task. However, the existence of PSR J0337+1715 provides an important piece of information: namely, that CE evolution (stage 2) not only leads to efficient orbital angular momentum loss of the inner binary orbit, also the tertiary star is subject to efficient in-spiral. The evidence for this conclusion is the following. On the one hand, the orbital period of the tertiary star could not be very large at the moment of the SN. There are two reasons for this: (1) the post-SN $P_{\rm orb,3}$ (after recircularization) must match the expected orbital period at the onset of the outer LMXB phase, and (2) to avoid a very small survival probability as a consequence of the SN. On the other hand, the system must have had $P_{\rm orb,3} \gtrsim 4000$ days on the ZAMS. The evidence for this is that the ratio of the orbital periods ($P_{\rm orb,3}/P_{\rm orb,12}$) on the ZAMS must have been at least a factor of $\sim$5, and even larger for noncircular orbits, in order for the triple system to remain dynamically stable on a long timescale (see Section 3.1). Furthermore, the onset of the CE could not have happened much earlier than near the tip of the RGB of the primary star, which corresponds to $P_{\rm orb,12} \gtrsim 800$ days. The reason is that the binding energy of the hydrogen-rich envelope is simply too high to allow for ejection at earlier stages (Dewi & Tauris 2000). This constraint, in combination with the stability criteria of the triple system, sets the lower limit of $P_{\rm orb,3} \sim 4000$ days on the ZAMS. Hence, we conclude that an efficient in-spiral of the tertiary star, and thus *both* of the outer stars, must have taken place.

Portegies Zwart et al. (2011) argued for a similar conclusion based on the tertiary F-dwarf orbiting the LMXB 4U 2129+47 (V1727 Cyg). As also pointed out by these authors, the SN explosion itself could also have decreased the orbital period of the tertiary star of the surviving triple system. In that case, the need for CE in-spiral is less extreme, but still highly demanded. From our simulations, we find that the pre-SN orbital period of the tertiary could have been up to about 120 days; still much shorter than the ZAMS $P_{\rm orb,3}$ of about 4000 days.

3. DISCUSSION

3.1. *Long-term Stability of a Triple System*

Throughout our scenario, we have checked at each evolutionary stage that the mutual orbits of our solutions are expected to have a long-term dynamical stability. A number of stability criteria for triple systems have been proposed over the last four decades (see Mikkola 2008, for an overview). To be extra cautious and conservative, we only accepted our found solutions in case they fulfilled all criteria suggested by Harrington (1972), Bailyn (1987), Eggleton & Kiseleva (1995), and Mardling & Aarseth (2001).

3.2. *Comparison to PSR J1903+0327*

The post-SN stages outlined here for the formation of PSR J0337+1715 differ somewhat from those proposed for PSR J1903+0327 (Champion et al. 2008; Liu & Li 2009; Freire et al. 2011; Portegies Zwart et al. 2011; Pijloo et al. 2012). The latter system most likely became dynamically unstable during a diverging LMXB evolution of the inner binary, as a result of the ($R_{\rm peri}/a_{\rm in}$) ratio decreasing below the critical limit (e.g., Mardling & Aarseth 2001) when the inner orbit expanded. This instability was possibly aided by cyclic perturbations of the inner binary by the unevolved tertiary star (Kozai 1962) while the critical orbital separation was approached. Hence, the J1903+0327 system may correspond to a disrupted case of an evolution which may otherwise have resulted in a triple MSP system.

3.3. *Alternative Models*

Despite its cold temperature, it cannot be excluded entirely that the outer WD formed last. The reason for this is that some low-mass helium WDs take 1–2 Gyr to reach the WD cooling track after detaching from their Roche lobe (A. Istrate et al., in preparation). Residual shell hydrogen burning cannot be ignored in these stars and keeps them hot on a long timescale (e.g., Alberts et al. 1996; Nelson et al. 2004). Since the duration of the outer LMXB phase is much shorter than that of the inner LMXB phase (15–20 Myr versus $\sim$2 Gyr, respectively; Tauris & Savonije 1999; Podsiadlowski et al. 2002), and given that a $\sim$0.4 $M_{\odot}$ helium WD does not experience residual hydrogen burning and therefore cools faster, it seems conceivable to form the outer WD *after* the formation of the inner WD. Even a double LMXB phase is possible, depending on how close in mass the two WD progenitor stars were, or if the secondary star was forced into RLO during mass transfer from the tertiary star.

de Vries et al. (2013) recently presented a novel attempt to simulate the combined stellar evolution, gravitational dynamics, and hydrodynamical interactions of a triple system. Although it is too early to draw firm conclusion from such a study, it is interesting to notice that their finding of significant loss of orbital angular momentum in the inner binary during the RLO from the tertiary star would strengthen the possibility of a double LMXB phase.

What are the alternative scenarios to the one presented here for producing PSR J0337+1715? A scenario with a massive star (M_1) orbited by a distant binary of low-mass stars (M_2, M_3) might be dynamically unstable during the CE stage. Instead, PSR J0337+1715 may possibly have formed in a quadruple system where the SN kick caused interactions with an outer binary and ejection of the fourth member.

The present triple system might also have evolved in a globular cluster and subsequently ejected into the Galactic field, for example, in a binary–binary encounter event. However, it is questionable if the triple system would survive such an ejection process. In addition, this scenario seems difficult to reconcile with the low eccentricities of PSR J0337+1715 and the fine match with the $M_{\rm WD}$–$P_{\rm orb}$ relation.

Finally, to obtain a small kick, one may advocate for the formation of the NS via accretion-induced collapse (AIC) of a WD (Nomoto et al. 1979). However, according to a recent study on AIC (Tauris et al. 2013), the required donor star masses are considerably larger ($\gtrsim 2\ M_\odot$, depending on metallicity) than what is constrained here for M_2.

4. FUTURE PROSPECTS AND CONCLUSIONS

We have presented a first self-consistent, semi-analytical solution to the formation of PSR J0337+1715 which constrains the peculiar velocity of the system to be less than 160 km s^{-1} and which requires double in-spiral during the CE evolution in a close triple system. We estimate that the uncertainties of our initial masses of all three stars are about 20%. We have briefly discussed a number of alternative models for which further calculations are needed. To probe the full parameter space with weighted probabilities for forming PSR J0337+1715 (depending on the pre-SN core mass, CE physics, orbital angular momentum losses, dynamical stability, geometry preferences for the mutual orbits, a possible quadruple origin, etc.) would require a full population synthesis investigation which is beyond the scope of this Letter.

PSR J0337+1715 is a unique example of a triple system which has survived *three* phases of RLO. The outcome of the two LMXB mass-transfer phases matches nicely with the theoretical expectations from the $M_{\rm WD}$–$P_{\rm orb}$ relation of WDs. The possibility of two RLO events in a triple system was first discussed by Eggleton & Kiseleva (1996) only two decades ago. These authors denoted such systems as "doubly interesting" triples. PSR J0337+1715 has not only managed to experience *three* phases of RLO, it has also survived a SN explosion to evolve toward its present terminal stage containing three compact objects—a truly remarkable journey for a triple system. Our analysis of the formation of this system only allows for a plausible solution when current knowledge of stellar evolution and interactions is stretched to the limit. The existence of this system in the Galactic field has opened a new door to stellar astrophysics with resulting challenges to be met in the years to come.

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