A formation scenario for the triple pulsar PSR J0337+1715: breaking a binary system inside a common envelope

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ABSTRACT

We propose a scenario for the formation of the pulsar with two white dwarfs (WDs) triple system PSR J0337+1715 where a close binary system is tidally and frictionally destroyed inside the envelope of a massive star that later goes through an accretion induced collapse (AIC) and forms the neutron star (NS). The proposed scenario includes a new ingredient of a binary system that breaks-up inside a common envelope. One of the two lower mass stars that ends further out transfers mass to the ONeMg WD remnant of the massive star, and triggers the AIC. The inner low mass main sequence star evolves later and spins-up the NS to form a millisecond pulsar. We use the binary_c software and show that both low mass stars end as helium WDs. This scenario is not extremely sensitive to initial conditions. For example, after the low mass binary system breaks loose inside the envelope, the tertiary stellar orbit can have any eccentricity, from a circular to a very eccentric orbit; it will in any case be circularized when the tertiary star turns into a giant. In addition, the secondary star final mass is determined by its core mass during its Hertzsprung gap phase. The proposed scenario employs an efficient envelope removal by jets launched by the compact object immersed in the giant envelope, and the newly proposed grazing envelope evolution.

1. INTRODUCTION

Despite much progress, e.g. review by Ivanova et al. (2013), the common envelope (CE) phase is one of the least understood processes in stellar binary evolution. The evolution becomes much more complicated if a close tertiary body exists in the system, such that the CE evolution includes three gravitating bodies. The evolution that formed the Galactic millisecond pulsar triple system PSR J0337+1715 might have gone through a CE phase involving three stars.

PSR J0337+1715 is a triple system that contains a 1.438M☉ radio millisecond pulsar (MSP) with a spin period of $P = 2.73$ ms orbited by two white dwarfs (WDs) (Ransom et al. 2014). The

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inner WD mass, orbital period, and eccentricity are $M_{\text{WD},2} = 0.197M_\odot$, $P_{1,2} = 1.63$ day, and $e_{1,2} = 6.9 \times 10^{-4}$, respectively, while those of the outer WD are $M_{\text{WD},3} = 0.410M_\odot$, $P_{12,3} = 327$ day, and $e_{12,3} = 0.035$. The system is coplanar to within $0.01^\circ$. Deeper study of the inner WD was conducted by Kaplan et al. (2014).

Tauris & van den Heuvel (2014) propose that the progenitor of PSR J0337+1715 contained a massive main sequence (MS) star of mass $\approx 10M_\odot$, orbited by two lower mass MS stars having masses and orbital periods of $1.1M_\odot$ and 835 day, for the inner star, and $1.3M_\odot$ and 4020 day for the outer stars. One after the other the two stars entered the bloated envelope of the massive star as it became a giant, and ended at very short orbital periods. The neutron star (NS) was formed by a core collapse supernova (CCSN) of the primary star. We see two problematic steps in this evolution. First, it is not clear how the two stars ended at short orbital periods. If the inner star managed to eject the envelope, as is assumed in the CE evolution, then there will be no envelope left to bring the outer tertiary star to a short orbital period. If on the other hand there is enough mass left in the primary envelope to swallow the tertiary star and bring it closer, then we expect the friction to cause the secondary star to collide with the primary core. The second problem is that NSs that are born in CCSNe are born with a non-zero velocity, called a kick velocity. It is very unlikely that the system will stay coplanar after a kick.

Triple star evolution have been proposed for binary pulsars (e.g. Freire et al. 2011; Pijloo et al. 2012; Portegies Zwart et al. 2011), such as the peculiar system PSR J1903+0327 (Champion et al. 2008). Freire et al. (2011) proposed that two MS stars were spiralling together in the envelope of the primary massive progenitor of the pulsar PSR J1903+0327. The inner companion was later destroyed or ejected, leaving behind the binary pulsar. Again, it is not clear that one envelope can cause substantial spiralling-in of two well separated stars (the secondary and the tertiary).

The problems we find in the scenario proposed by Tauris & van den Heuvel (2014) motivate us to consider a different scenario, also involving a CE phase with three stars, for the formation of PSR J0337+1715. The large fraction of triple systems among binary stars, e.g., Rappaport et al. (2013) who argue that at least 20% of all close binaries have tertiary companions, further motivates us to consider different types of triple systems than previously proposed models for binary and triple pulsar systems. In section 2 we describe our proposed scenario. The new ingredient we introduce, of breaking-up a close binary system inside a CE, is presented in section 3. In section 4 we study the evolution of the secondary and tertiary stars to form WDs. Our discussion and summary are in section 5.
2. THE SCENARIO

The proposed scenario is described schematically in Fig [1] and parameters for one case studied here with binary [Izzard et al. 2004, 2006, 2009, section 4] are listed in Table 1. The initial triple-star system is composed from a primary star, the initially more massive main sequence (MS) star, and a tight binary system of lower mass MS stars. The outer binary system is tight in the sense that the orbital separation of the two outer stars is much smaller compared to the orbital separation between their center of mass and the massive star. The interaction starts when the primary star becomes a giant, and its envelope tidally interacts with the tight binary system.

We divide the evolution of the system into five main stages separated by four phases of strong stellar interaction. Here we describe the four interaction phases. The first one is further discussed in section 3, and the last three interaction phases are studied in section 4.

(1) Tidal break-up inside a common envelope. The first stage is the most delicate one, as we suggest that two processes occur simultaneously: The chaotic process of tidal break-up and the poorly understood common envelope (CE) evolution. We start (phase I in Fig [1]) with a triple system composed of three MS stars of masses $M_{1,i} \approx 7.5 - 8.5 M_\odot$, $M_{2,i} \approx 0.9 - 1.2 M_\odot$, and $M_{3,i} \approx 1.3 - 1.4$, which we term the primary, secondary and tertiary, respectively. The two lighter stars form a tight binary system, for which we estimate the initial orbital separation for a circular (or low eccentricity) orbit to be $a_{2,3,i} \approx 50 - 100 R_\odot$. This estimate will have to be checked with a three-body numerical code that includes tidal interaction and mass removal by jets from the two stars. This is way beyond the scope of this paper. The primary evolves and suffers two expansion episodes, when it has a helium core and later when the core is made up mainly from CO. Because of tidal interaction, most likely the CE occurs in the first expansion episode (phase II in Fig [1]). The outer binary system enters the envelope of the giant, spirals-in, and removes the hydrogen-rich envelope.

As the outer binary spirals in, it breaks apart because of tidal interaction. We estimate this to occur when the center of mass of the outer binary is at $a_{1,23} \approx a_{2,3} \approx 100 R_\odot$ from the center of the primary. The secondary star, the lighter one, loses angular momentum more efficiently and spirals-in to an orbital separation of $\approx 50 - 70 R_\odot$ ($60 R_\odot$ in the case studied here), from the 2.4 $M_\odot$ He core of the primary, now having a radius of few $\times R_\odot$. The tertiary star ends further out. This is further discussed in section 3.

(2) AGB interaction. As the primary continues to evolve and forms an ONe core (phase IV in Fig [1]), the secondary is as massive as the primary’s envelope and is able to bring it to co-rotation, enhance the mass loss rate [Tout & Eggleton 1988] and expel the entire envelope of the primary (phase V in Fig [1]). Moreover, it is possible that the secondary accretes mass through an accretion disk and launches two opposite jets that expel part of the primary He-rich envelope.
(Soker 2014, 2015). If a CE prescription is used, like what we will do later, then the removal of an envelope by spin-up and jets leads to an effective value of the $\alpha_{CE}$ parameter that is larger than unity, $\alpha_{CE-eff} > 1$. At the end of this phase of evolution the primary forms a $1.25 - 1.4M_\odot$ ONeMg WD, and the triple system has the properties listed in the fourth column of Table 1 for a case study. These parameters are justified in the next two sections. In the table, circular orbits are assumed for the initial system.

**Table 1: Stellar evolution of a case study**

|               | Initial | post break-up | post primary-AGB | post AIC | final stage | Observed |
|---------------|---------|---------------|------------------|----------|-------------|----------|
| $M_1(M_\odot)$ | 8 (MS)  | 2.4 (He star) | 1.4 (ONe WD)     | 1.5 (NS) | 1.5 (NS)    | 1.4378   |
| $M_2(M_\odot)$ | 1 (MS)  | 1 (MS)        | 1 (MS)           | 1.18 (MS)| 0.2 (He WD) | 0.1975   |
| $M_3(M_\odot)$ | 1.4 (MS)| 1.4 (MS)      | 0.41 (He WD)     | 0.41 (He WD) | 0.4101 |
| $a_{inner}[R_\odot]$ | $a_{2:3,i} \approx 50 - 100$ | $a_{1:2, BU} = 60$ | $a_{1:2, pAGB} = 18.3$ | $a_{1:2, pAIC} = 16.5$ | $a_{1:2, f} = 6.3$ | 6.83 |
| $a_{outer}[R_\odot]$ | $a_{1:2,3,i} \approx 200 - 400$ | $a_{12:3, BU} = 214$ | $a_{12:3, pAGB} = 270$ | $a_{12:3, pAIC} = 157$ | $a_{12:3, f} = 231$ | 252.5 |
| Comments | $e_{2:3,i} = 0$ | $e_{1:2, BU} = 0.5$ | $e_{1:2, pAGB} = 0$ | $e_{1:2, pAIC} = 0$ | $e_{1:2,3, f} = 0$ |

The masses and orbital separations of the triple system PSR J0337+1715 at the main phases of the evolution, for a case study calculated with $binary_{CE}$ (Izzard et al 2004, 2006, 2009). Circular orbits are assumed for the initial setup. The table shows an example of one case study with certain initial parameters (column 2; phase I in Fig[1]) out of the allowed parameter range given in the text, e.g., the primary initial mass $M_{1,i} \approx 7.5 - 8.5M_\odot$, secondary initial mass $M_{2,i} \approx 0.9 - 1.2M_\odot$, and tertiary initial mass $M_{3,i} \approx 1.3 - 1.4$. The post break-up (BU) properties are listed in column 3 (phase III in Fig[1]). Note the exchange of inner and outer binary stars from the initial stage to the post break-up stage: The initial tight binary is composed of the secondary and tertiary stars, whereas after the break-up of the secondary - tertiary binary system inside the common envelope, the primary and secondary stars become the inner binary system. The post primary-asymptotic giant branch (pAGB) properties are listed in column 4 (phase V in Fig[1]), where we find the allowed primary post-AGB mass to range over $M_{1,pAGB} \approx 1.25 - 1.4M_\odot$. During the following evolution phase of the tertiary (phase VI in Fig[1]) we find with $binary_{CE}$ that the tertiary transfers a mass of $M_{accret} = 0.55M_\odot$ via RLOF to the inner binary. We take $0.44M_\odot$ to be accreted by the central binary system taking into account mass loss by jets in the accretion disk around the inner binary. Consequently, the primary experiences an AIC and forms a NS. We assume its mass is reduced due to energy carried by neutrinos emitted by the cooling NS. The post AIC parameters are listed in column 5 (phase VIII in Fig[1]). The next stage is the evolution of the secondary star, (phase IX in Fig[1]) after which the system reaches its final stage (column 6; phase X in Fig[1]) that corresponds with the observed parameters of the system (column 7).

(3) Tertiary evolution. As the tertiary evolves and becomes an evolved RGB star it interacts with the inner binary system, now composed of an ONeMg WD and a MS star (phase VI in Fig[I]). Two processes take place and lead to the next stage of the triple system that we term post tertiary. The first is tidal interaction that leads to the circularization of the orbit, even if the orbit is very eccentric. For an eccentricity of $e_{12:3, pAGB} = 0.8$ we find the required semimajor axis before the evolution of the tertiary (the post primary-AGB stage) to be $a_{1:2:3, pAGB} \approx 550R_\odot$. This implies
a periastron distance of \( \approx 110R_\odot \) which leads to a very strong tidal interaction near periastron passages and subsequently to a circular orbit. These parameters will bring the final result of our simulation even closer to the observed parameters of the system.

The second process is mass transfer. We find the mass transfer to be sufficient to cause the ONeMg WD to overpass the Chandrasekhar mass limit and suffer an AIC (e.g., Ablimit & Li 2014, for a recent paper). The tertiary mass can be fitted to the observed value, as we show in section 4. The mass transfer increases also the mass of the secondary star and leads to the shrinkage of the orbit of the inner binary system (phase VII in Fig[I]).

(4) Secondary evolution. The observed mass of the secondary star is \( 0.1975M_\odot \), and it is a He WD. This fits the core of a low mass star during its evolution on the Hertzsprung gap. In our scenario the secondary and the NS strongly interact when the secondary evolves in the Hertzsprung gap (phase IX in Fig[I]). This dictates the orbital separation prior to this phase to be \( a_{1,2,pAIC} \approx 15.5 - 18.5R_\odot \). This is a much smaller radius than the maximum radius of the star on the RGB, and a CE phase takes place in addition to the strong tidal interaction. The tidal interaction and CE evolution explain the observed circular orbit. To account for the observed (final) orbital separation of the inner binary, \( a_{1,2} \approx 6.8R_\odot \), the CE must be very efficient in removing the envelope. Jets blown by the NS can account for \( \alpha_{CE-eff} > 1 \). The process might even be a grazing envelope evolution (GEE; Soker 2015; see next section) rather than a CE evolution, which implies an even larger value of \( \alpha_{CE-eff} \) (although this is not a real CE phase). Over all, when we use binary (section 4), we can justify taking \( \alpha_{CE-eff} > 1 \). During this phase the secondary loses mass, a small fraction of which is accreted by the NS, the orbital separation of the inner binary decreases and that of the tertiary increases. The final masses and orbital separations are listed in Table I.

3. BINARY INSIDE A COMMON ENVELOPE

The tight binary system (the two lower mass MS stars) tidally breaks up approximately when the orbital separation of its center of mass from the primary is (Miller et al. 2005; Sesana et al. 2009)

\[
a_{1,23} \approx \left( \frac{3M_{1,i}(a_{1,23})}{M_{2,3:i}} \right)^{1/3} a_{2,3}.
\]

(1)

The ratio of orbital periods at that epoch is

\[
\frac{P_{1,23}}{P_{2,3}} \approx \left( \frac{a_{1,23}}{a_{2,3}} \right)^{3/2} \left( \frac{M_{1,i}(a_{1,23}) + M_{2,3:i}}{M_{2,3:i}} \right)^{-1/2} \approx 3^{1/2} \left( \frac{M_{1,i}(a_{1,23})}{M_{1,i}(a_{1,23}) + M_{2,3:i}} \right)^{1/2} \approx 1.5,
\]

(2)

where \( M_{1,i}(a_{1,23}) \) is the primary mass inner to the location of the tight binary, \( a_{1,23} \), and \( M_{2,3:i} \) is the combined initial mass of the secondary and tertiary stars. From this condition it is clear that to
reach tidal break-up the tight binary must spiral-in such that the orbit \( a_{1,23} \) shrinks faster than the orbit of the tight binary system \( a_{2,3} \). We now discuss the condition for this to occur.

The tight binary system loses angular momentum of motion around the primary star inside the envelope within a few dynamical times. This implies that the tidal break up occurs on a scale not much shorter than the spiraling-in time. Both processes must be considered simultaneously. We can safely say that the friction force of the two MS stars in the envelope cannot be neglected. If one of the two MS stars is ejected within the envelope it might lose momentum and stay bound, even if the star is ejected with an initial velocity above the escape velocity. As we later show, even a very high eccentricity of the outer star’s orbit, \( e \sim 0.8 \), will lead to the desired outcome. In a tidal-break up usually the lower mass companion of the binary is ejected. Inside the CE, however, dynamical friction with the envelope must be considered. The outcome might be that the lower mass companion of the tight binary is spiraling-in deeper and the heavier companion ends on a larger orbit, particularly since the difference in mass between the two MS stars is not large.

From preliminary simulations (Michaeli, E., 2015, private communication) it turns out that when the tight binary is immersed in the undisturbed giant envelope the tight binary system becomes even harder (its orbit shrinks), and no tidal break-up occurs. The gravitational drag causes both MS stars to lose energy, such that the orbital separation between them becomes tighter faster than the time on which their distance from the core of the giant star shrinks. In such a case no tidal break-up occurs. However, if roughly only the star closer to the giant’s core suffers from gravitational drag, tidal break-up can occur. The way to substantially reduce the drag on the outer MS of the tight binary system is to remove the envelope outside the orbit of the tight binary system. The tight binary system actually experiences a grazing envelope evolution (GEE; Soker 2015) rather than a true CE evolution. In the GEE the binary system might be considered to evolve in a state of “just entering a CE phase”. The companion star in a regular binary system, or the tight binary system in the tertiary case, removes the envelope beyond its orbit by launching jets (Soker 2014). The removal of the envelope outside the orbit prevents the formation of a full CE phase. This efficient envelope removal increases the effective value of the CE parameter to values of \( \alpha_{CE} > 1 \) (even though no real CE takes place, but rather a GEE).

### 4. FORMING THE PULSAR AND THE TWO WHITE DWARFS

We use the population nucleosynthesis code \textit{binary} \( c \) of Izzard et al (2004, 2006, 2009) based on the Binary Star Evolution (BSE) code of Hurley et al (2002). To treat the triple system, for each phase of strong interaction we simulate a binary system. We give a representative case for the scenario, and later show that there is no need here for fine tuning. At the post CE break-up phase of the system (phase III in Fig 1) the primary is a He star of mass \( M_{1,BU} = 2.4M_\odot \) in an inner
binary with the secondary star of $M_{2,BU} = 1M_\odot$. The primary continues to evolve and forms an ONe core in the mass range of $M_{1:pAGB} \approx 1.25 - 1.4M_\odot$ as it expands along the AGB (phase IV in Fig.1).

Now starts another phase of strong binary interaction. The secondary is massive enough to bring the primary envelope to co-rotation, and hence enhances the mass loss rate from the primary, up to a factor $\gtrsim 100$, e.g., Tout & Eggleton (1988). Another process that can aid in removing the primary He-rich envelope is the launching of jets by the MS companion (Soker 2014, 2015). This stage of interaction with tidally-enhanced mass loss rate and possible jets can not be modelled correctly with the \textit{binary.c} code. We can only mimic these processes by taking the $\alpha_{CE}$ parameter at this stage to be larger than unity. We here take $\alpha_{CE} = 5$. From examining other values we estimate that to reach the observed parameters of the PSR J0337+1715 system, the inner binary separation at the post CE break-up phase should be in the range of $\approx 50 - 70R_\odot$. Once the entire envelope of the primary is ejected it forms an ONe WD, while the secondary star remains a MS star (phase V in Fig.1). We term this phase the post primary-AGB phase of the system and we estimate the separation of the inner binary at this stage to be $a_{1,2:pAGB} \approx 17.5 - 20.5R_\odot$.

We consider a case study for an example of a possible evolution. We take the immediately post primary-AGB system to be composed of an ONeMg WD of mass $M_{1:pAGB} = 1.4M_\odot$, and two MS stars with masses of $M_{2:pAGB} = 1.0M_\odot$ and $M_{3:pAGB} = 1.4M_\odot$. The orbital separation of the inner MS star and the ONeMg WD is $a_{1,2:pAGB} = 18.3R_\odot$, and that of the tertiary star from the center of mass of the inner binary is $a_{3:pAGB} = 270R_\odot$. Circular orbits are assumed for the representative case.

We first follow the evolution of the outer MS star—the tertiary star, as it is more massive than the secondary star. For the usage of \textit{binary.c} we need to treat the inner binary (the ONeMg WD + the low mass MS secondary star) as one star when following the evolution of the outer MS star. Numerically we take the inner binary system as a compact body of mass $M_{in-binary:pAGB} = M_{1:pAGB} + M_{2:pAGB} = 2.4M_\odot$, and examine how much mass it accretes from the evolving tertiary star (Technically we take it as a NS in \textit{binary.c}). As the tertiary star evolves and fills its Roche Lobe, it transfers a part of its envelope to the inner binary. To account for the mass loss enhancement from the rotation around the massive inner binary (Tout & Eggleton 1988), we take the Giant Branch wind multiplier to be $= 10$ in \textit{binary.c}. The tertiary ends this phase of evolution as a He WD of mass $M_{3:f} = 0.41M_\odot$; this will be its final mass.

With \textit{binary.c} we find that the tertiary star transfers a mass of $M_{acc:t} = 0.55M_\odot$ via RLOF to the inner binary (phase VI in Fig.1). Some fraction, $0.05 - 0.3$, of this mass might be blown away by jets launched by the accretion disks around the two stars. For that, we take $0.44M_\odot$ to be accreted by the central binary system. We assume the mass accreted according to the mass of each star; the secondary, $M_2$, accretes $0.18M_\odot$ whereas the ONe WD, $M_1$, accretes $0.26M_\odot$.
and experiences an AIC to form a NS of mass $M_{\text{NS:pAIC}} \approx 1.5 M_\odot$. The reduction in mass is due to energy carried by neutrinos emitted by the cooling NS. Considering the mass loss to jets and neutrinos, the orbital separation of the tertiary star from the center of mass of the inner binary is somewhat larger than what the binary $\alpha$ simulation gives. We find the separation at the end of the tertiary evolution and AIC stage to be $a_{12,3:pAIC} = 157 R_\odot$ (phase VIII in Fig.1). The inner binary system is composed now of a NS of mass $M_{1:pAIC} = 1.5 M_\odot$ and a MS star of mass $M_{2:pAIC} = 1.18 M_\odot$ orbiting each other with an orbital separation of $a_{12:pAIC} = 16.5 R_\odot$.

We next run binary $\alpha$ for the inner system as the secondary star evolves off the main sequence and into the Hertzsprung gap and forms a He core (phase IX in Fig.1). This CE phase must be very efficient in removing the secondary envelope due to jets blown by the NS. Similar to the AGB interaction phase, we can only mimic this high efficiency by taking a high value of $\alpha_{\text{CE}}$; we here take in the case study $\alpha_{\text{CE}} = 10$. At the end of this stage we find in our case study the final masses of the NS and the secondary star, now a He WD, to be $M_{\text{NS:f}} = 1.5 M_\odot$, and $M_{2:f} = 0.2 M_\odot$, respectively, and their orbital separation to be $a_{12:f} = 6.3 R_\odot$. Due to the mass loss by the inner binary system, the orbital separation of the tertiary star increases from $a_{12,3:pAIC} = 157 R_\odot$ to $a_{3:f} = 231 R_\odot$. This is the final, and observed, stage of the system (phase X in Fig.1; sixth column of Table 1). The masses and orbital separations at the five phases are summarized in Table 1.

We note that due to some uncertainties in some of the processes, e.g., how much mass is lost in the accretion process onto the NS, the final parameters, e.g., final mass of the NS, are not certain. Therefore some differences between our derived final parameters and the observed ones are not significant. Such is the difference between the observed NS mass and our value in the case study, $1.438 M_\odot$ and $1.5 M_\odot$, respectively.

Using the binary $\alpha$ code for different post primary AGB parameters of the triple system, we find that there is flexibility in setting the initial parameters to achieve the observed PSR J0337+1715 system. Namely, there is no need to fine tune the parameters that can span the following ranges; $M_{1:pAGB} \approx 1.25 - 1.4 M_\odot$, $M_{2:pAGB} \approx 0.9 - 1.2 M_\odot$, $M_{3:pAGB} \approx 1.3 - 1.4 M_\odot$, $a_{12,3:pAGB} \approx 260 - 300 R_\odot$ and $a_{12,2:pAGB} \approx 17.5 - 20.5 R_\odot$. We also find that a tertiary post primary-AGB eccentric orbit can be circularized as the tertiary becomes a giant and tidally interacts with the inner binary. For example, taking for the post primary-AGB tertiary orbit an eccentricity and semimajor axis of $e_{12,3:pAGB} = 0.8$ and $a_{12,3:pAGB} \approx 550 R_\odot$, respectively, leads to the desired post-tertiary parameters. The reason is the strong tidal interaction at periastron passages during the RGB phase of the tertiary star.

The final mass of the secondary star of $\approx 0.2 M_\odot$ does not depend much on the post primary-AGB separation as well. It comes from the core mass of $\approx 0.9 - 1.2 M_\odot$ stars evolving along the Hertzsprung gap. During the Hertzsprung gap star substantially expands, and a strong interaction with the NS companion starts and removes the secondary envelope. We use the Modules
for Experiments in Stellar Astrophysics (MESA), version 5819 (Paxton et al. 2011) to evolve few models that are presented in Fig. [2] For a star with a ZAMS mass in the range \( \approx 0.9 \sim 1.2 M_\odot \) the first large expansion occurs when the He core mass is in the range \( \approx 0.19 \sim 0.2 M_\odot \).

5. SUMMARY

We proposed a scenario for the triple system PSR J0337+1715 composed of a pulsar orbited by two white dwarfs (Ransom et al. 2014; Kaplan et al. 2014; Tauris & van den Heuvel 2014). Our proposed scenario is described in Fig. [1] and the values for a case study at the different evolutionary phases are given in table [1].

The triple pulsar system PSR J0337+1715 raises two puzzles. (1) What initial setting can lead to a very close inner white dwarf (WD), the secondary, orbiting a pulsar, and a WD, the tertiary, at an orbital separation of about the size of a giant star. It is clear that the secondary WD could not have evolved through a regular common envelope (CE) phase without the influence of the tertiary star. (2) The triple system is coplanar, indicating that no violent event could have taken place, and the system started coplanar. This suggests that the neutron star (NS) was formed by accretion induced collapse (AIC) rather than by a core collapse supernova. We propose that the AIC is caused by mass transfer from the tertiary star during its red giant phase (phases VI-VIII in Fig. [1]).

To solve these puzzles we have introduced to the scenario two new ingredients. The first one is the entrance of a relatively close binary system (the tight binary system) into the envelope of the primary star during its giant phase. Namely, the two lower-mass stars enter the primary envelope together, rather than one after the other as in the scenario of Tauris & van den Heuvel (2014). The second new ingredient is the process of grazing envelope evolution (GEE; Soker 2015).

We assumed that the secondary-tertiary tight binary system evolves in a GEE, such that the giant primary envelope outside the center of mass of the tight binary system is removed. The spiralling-in process while grazing the giant envelope is a GEE. Namely, the outer star, or a tight binary system, is evolving in a ‘just enters a CE phase’. Jets launched by the compact companion, or by one or two of the stars in a tight binary, remove the giant envelope outside the orbit. If one is to use the \( \alpha_{CE} \) parameter, then this efficient envelope removal increases the effective value of the CE parameter to values of \( \alpha_{CE} > 1 \). In the tight binary system only the star that is closer to the center of the primary star suffers the full gas dynamical friction by the envelope. The other star is in a region where the envelope gas has been removed already. We consider here an outcome where the tight inner binary spirals-in and tidally breaks-up, such that the lighter secondary star in-spirals and forms a binary system with the massive primary core, whereas the heavier tertiary star ends on a larger orbit.
We then used the binary numerical code (Izzard et al. 2004, 2006, 2009) to further evolve the system, first the tertiary star and then the secondary star, as described in section 4. Here as well we had to assume that tidal spin-up and/or jets launched by the compact star aid in removing the envelope. This implies that we can use a value of \( \alpha_{\text{CE}} > 1 \). We used values of \( \alpha_{\text{CE}} = 5 \) and \( \alpha_{\text{CE}} = 10 \). It is quite possible that during the later CE phases, IV and IX in Fig. 1 not only do the jets aid in removing the envelope, but the jets are very efficient in doing so as to lead to a GEE (Soker 2015), at least during part of the strong interaction phase. We also showed that no fine tuning is required to achieve the triple system PSR J0337+1715 when one considers tidally enhanced mass loss and jet-removal of the envelope.

Our results have more general implications in showing that a common envelope with a binary system entering the envelope of a giant star can lead to a rich variety of evolved triple systems. The survivability of the three stars in such an evolution can be accounted for if the removal of an envelope of a giant star with tidal spin-up and jets is considered.

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This preprint was prepared with the AAS LaTeX macros v5.2.
I. Initial state
(2nd column in Table 1)

II. CE break-up

III. Post CE break-up
(3rd column in Table 1)

IV. AGB interaction

V. Post primary-AGB
(4th column in Table 1)

VI. Tertiary evolution

VII. Post tertiary

VIII. Post AIC
(5th column in Table 1)

IX. Secondary evolution

X. Final
(6th column in Table 1)

Fig. 1.— The evolution of the triple system from the initial setup where all three stars are on the main sequence (MS) and until the current observations. Note that in our notation the initial mass of the tertiary star is larger than that of the secondary star: $M_{1,i} > M_{3,i} > M_{2,i}$. The colors are as follows: grey is for the primary star, blue for the secondary star and red for the tertiary star. As each star reaches a more advanced evolutionary stage its color darkens. The evolution from phases I to III is assumed here. The evolution there after (phases III - X) is calculated with binary. Binary.
The core mass $M_\odot$.

He frac. 50 $R_{\text{He core}}$

Fig. 2.— The evolution of a $0.9 - 1.2M_\odot$ star calculated with MESA (Paxton et al. 2011), from zero-age main sequence (ZAMS) until the first expansion phase where the star has a He core, as a function of the He core mass. The colors are as follows: blue is for a $0.9M_\odot$ star, red is for a $1.0M_\odot$ star, green is for a $1.1M_\odot$ star and purple is for a $1.2M_\odot$ star. The thick solid black line depicts the radius of the He core for the case of a $1.0M_\odot$ star. The left vertical axis relates to the radius of the star (thin solid lines) and the radius of the He core (thick solid black line), and the right vertical axis relates to the He fraction in the core (dashed lines). It is evident that the first large expansion of the star occurs for all models when the He core mass is $\approx 0.19 - 0.2M_\odot$. This explains the mass of the secondary star in the PSR J0337+1715 system according to our scenario.