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Formation of long-period post-common-envelope binaries: no extra energy is needed to explain oxygen-neon white dwarfs paired with AFGK-type main-sequence stars

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Abstract. It has been claimed for decades that energies other than orbital and thermodynamic internal are required to explain post-common-envelope binaries (PCEBs) with long orbital periods hosting AFGK-type main-sequence (MS) stars paired with oxygen-neon (ONe) white dwarfs (WDs). This would imply a completely different energy budget during CE evolution for these PCEBs in comparison to the remaining systems hosting M dwarfs and/or less massive WDs. We carried out binary population simulations with the BSE code adopting empirically derived inter-correlated MS binary distributions and assuming that the only energy, in addition to orbital, that helps to unbind the CE is thermal energy. Unlike what has been claimed for a long time, we show that all such PCEBs can be explained by assuming inefficient CE evolution, which is consistent with results achieved for the remaining PCEBs. There is therefore no need for an extra energy source. For all known systems we found formation pathways consisting of CE evolution triggered when a highly evolved, thermally pulsing, asymptotic giant branch star fills its Roche lobe at an orbital period of several thousand days. Due to the sufficiently low envelope mass and sufficiently long orbital period, the resulting PCEB orbital period can easily be several tens of days. We conclude that the known PCEBs with ONe WDs and AFGK-type MS stars can be explained without invoking any energy source other than orbital and thermal energy. Our results strengthen the idea that the most common formation pathway of the overall population of PCEBs hosting WDs is through inefficient CE evolution.

Resumo. Há décadas, tem sido afirmado que energias diferentes da orbital e da interna termodinâmica são necessárias para explicar binárias pós-envelope-comum (PCEBs) com longos períodos orbitais hospedando estrelas da sequência principal (MS) do tipo AFGK pareadas com anãs brancas (WDs) de oxigênio-neônio (ONe). Isso implicaria um balanço energético completamente diferente durante a evolução de envelope comum para esses PCEBs em comparação aos sistemas restantes que hospedam anãs M e/ou WDs menos massivas. Realizamos simulações de populações de binárias com o código BSE adotando distribuições de binárias MS intercorrelacionadas derivadas empiricamente e assumindo que a única energia, além da orbital, que ajuda a ejetar o envelope comum é a energia térmica. Ao contrário do que se afirma há muito tempo, mostramos que todas essas PCEBs podem ser explicadas assumindo uma evolução ineficiente de envelope comum, o que é consistente com os resultados obtidos para as PCEBs restantes. Portanto, não há necessidade de uma fonte de energia extra. Para todos os sistemas conhecidos, encontramos caminhos de formação consistindo de evolução de envelope comum desencadeada quando uma estrela gigante do ramo assintótico, altamente evoluída e pulsante termicamente preenche seu lóbulo Roche em um período orbital de vários milhares de dias. Devido à massa do envelope suficientemente baixa e ao período orbital suficientemente longo, o período orbital da PCEB resultante pode facilmente ser de várias dezenas de dias. Concluímos que as PCEBs conhecidas com WDs do tipo ONe e estrelas MS do tipo AFGK podem ser explicadas sem invocar fonte de energia alguma além das energias orbital e térmica. Nossos resultados fortalecem a ideia de que o caminho de formação mais comum da população geral de PCEBs que hospedam WDs é por meio de evolução ineficiente de envelope comum.

Keywords. stars: AGB and post-AGB – binaries: general – methods: numerical – stars: evolution – white dwarfs

1. Introduction

Most close binaries containing stellar remnants are believed to form during common-envelope (CE) evolution (e.g. Paczynski 1976; Ivanova et al. 2013; Belloni & Schreiber 2023), in which friction drastically reduces the orbital separation and part of the orbital energy is used to unbind the CE, leaving the exposed core of the giant and its companion in a much tighter orbit. Post-CE binaries are thus close binaries that survived the engulfment of a star by the deep convective envelope of a companion that filled its Roche lobe when it was a red giant.

In most cases, i.e., for initial masses below $\sim 8 - 10$ M$_\odot$, the core of the red giant will cool down to become a white dwarf (WD). If the Roche lobe was filled during the first ascent on the red giant branch (FGB) it will be a low-mass ($\lesssim 0.5$ M$_\odot$) helium-core WD or a low-mass ($\sim 0.32 - 0.47$ M$_\odot$) hybrid carbon-oxygen-core WD (as helium contributes by a non-negligible fraction to their masses) if it experienced a phase of core helium burning (as a helium star) after losing the envelope (e.g. Heber 2016). On the other hand, if the Roche lobe was filled during the asymptotic giant branch (AGB), the resulting WD will be more massive ($\gtrsim 0.5$ M$_\odot$) and typically composed of carbon-oxygen. If the progenitor star was massive enough to reach a core mass of $\gtrsim 1.1$ M$_\odot$, the carbon in the core can be converted to oxygen and neon and consequently the emerging WD would be made of the latter.

Companions to WDs in observed post-CE binaries can be either unevolved stars (i.e. main-sequence stars), stellar remnants (i.e. helium stars, WDs, neutron stars or black holes), red giants or subgiants (that most likely were on the main sequence during CE evolution and evolved after the post-CE binary was already formed), brown dwarfs (Zorotovic & Schreiber 2022) or even planets (e.g. Lagos et al. 2021). Throughout this work, we considered only post-CE binaries consisting of WDs with main-sequence star companions that did not experience mass transfer, that is, an episode of mass transfer in addition to CE evolution in which the main-sequence stars are donors. Such systems are most suitable for constraining CE evolution as their stellar and orbital parameters have been shaped by CE evolution alone.

Previous attempts to reconstruct the CE phase for observed post-CE binaries have found that the vast majority of systems, with typical orbital periods of hours to a few days, can be explained assuming inefficient CE evolution (e.g. Zorotovic et al. 2010; Toonen & Nelemans 2013; Camacho et al. 2014; Cojocaru et al. 2017; Belloni et al. 2019; Hernandez et al. 2022; Zorotovic & Schreiber 2022; Scherbak & Fuller 2023; Ge et al. 2024). However, there are currently several systems with orbital periods of from a few tens to a few hundreds of days. These periods are much longer than those of most post-CE binaries (Nebot Gómez-Morán et al. 2011) but too short to be the result of dynamically stable mass transfer. It has been claimed that these long-period post-CE binaries cannot be explained by CE evolution without contributions from additional energy sources in the CE energy balance (e.g. Davis et al. 2010; Zorotovic et al. 2010, 2014; Yamaguchi et al. 2024a). To solve this issue, it has been suggested that a small fraction of the available hydrogen recombination energy decreases the binding energy of the CE. However, it remains a topic of intense discussion whether recombination energy can have any impact on the CE ejection or not (e.g. Soker & Harpaz 2003; Ivanova et al. 2013; Ivanova 2018; Soker et al. 2018; Grichener et al. 2018; Röpke & De Marco 2023; Belloni & Schreiber 2023).

We here investigate whether CE evolution generated when the WD progenitor was a thermally-pulsing AGB (TP-AGB) star can explain the characteristics of the observed long-period systems. We considered all observationally characterised binaries with sufficiently long orbital periods (> 1 d), massive WDs (> 1.1 M$_\odot$), main-sequence stars of type earlier than M (> 0.5 M$_\odot$), and low-eccentricity orbits (< 0.1). In particular, we carried out binary population models to investigate whether extra energies are required or not to explain their properties. We found that extra energy is not required to explain post-CE binaries with orbital periods as long as a thousand days. Instead, we present reasonable formation pathways for all considered post-CE binaries assuming inefficient CE evolution. Here, we present a summary of this work, which was published in Belloni et al. (2024b).

2. Observational Sample

There are currently six known post-CE binaries with long orbital periods ($\gtrsim$ 1 d), oxygen-neon WDs ($\gtrsim$ 1.1 M$_\odot$) and AFGK-type main-sequence stars. In what follows, we provide a brief discussion of the characteristics of these systems.

IK Peg (also known as HR 8210, HD 204188 or J 2126+193) was the first member of this class of post-CE binaries. It hosts a main-sequence star of spectral type A8 ($\sim$ 1.7 M$_\odot$). IK Peg was discovered as a single-lined spectroscopic binary almost a century ago. Combining Harper's data with more recent observations, Vennes et al. (1998) refined the orbital period measurement (21.72168 ± 0.00009 d) and confirmed the orbit to be circular. The WD nature of the unseen companion (named EUVE J2126+193) was established in the 1990s, having an estimated mass of $1.15^{+0.05}_{-0.15}$ M$_\odot$.

Yamaguchi et al. (2024a) recently presented five newly discovered post-CE binaries containing massive WD candidates ($\gtrsim$ 1.2 M$_\odot$) and main-sequence stars with spectral types earlier than M ($\gtrsim$ 0.7 M$_\odot$) with long orbital periods (20 − 50 d). These systems were discovered as part of a broader search for compact object binaries from the *Gaia* DR3 non-single star catalogue and, considerably extended the sample of such binaries.

3. Binary Population Models

We carried out post-CE binary population synthesis with the BSE code (Hurley et al. 2002) adopting the methodology described in detail in Belloni et al. (2024a). Briefly, we selected $\approx 6.15 \times 10^5$ zero-age main-sequence binaries and picked the primary mass from the canonical Kroupa (2001) initial mass function in the range between 1 and 8 M$_\odot$. We used the correlated distributions derived by Moe & Di Stefano (2017), in which the orbital period distribution depends critically on the primary mass and the binary fraction and the eccentricity and mass-ratio distributions depend on both orbital period and primary mass. These fitted correlated distributions are the most realistic ones currently available and should be incorporated into binary population models.

For this work, the treatment of CE evolution in BSE is crucial. This phase is usually approximated by a simple equation introduced in the eighties (Webbink 1984; Livio & Soker 1988) in which the binding energy of the envelope of the red giant donor ($E_{\rm bind}$) at the onset of the CE evolution is assumed to be equal to the change in orbital energy during the spiral-in phase ($\Delta E_{\rm orb}$) scaled with a parameter α, which corresponds to the fraction of the change in orbital energy that is used to unbind the envelope. We adopted the relation put forward by Iben & Livio (1993), i.e.,

$$E_{\rm bind} \;=\; \alpha\, \Delta E_{\rm orb} \;=\; -\,\alpha \left(\frac{G\, M_{\rm d,c}\, M_{\rm a}}{2\, a_f} \;-\; \frac{G\, M_{\rm d,c}\, M_{\rm a}}{2\, a_i} \right), \quad (1)$$

where G is the gravitational constant, $E_{\rm bind}$ is the donor envelope binding energy, $E_{\rm orb}$ is the orbital energy, $M_{\rm a}$ is the accretor mass, $M_{\rm d,c}$ is the core mass of the donor, a_i is the semimajor axis at the onset of the CE evolution, and a_f is the semimajor axis after CE ejection.

The binding energy is usually approximated by

$$E_{\rm bind} \;=\; -\,\frac{G\, M_{\rm d}\, (M_{\rm d} \;-\; M_{\rm d,c})}{\lambda\, R_{\rm d}}\,, \quad (2)$$

where $M_{\rm d}$ is the donor mass, $R_{\rm d}$ is the donor radius, and λ is the envelope-structure parameter, which depends on the structure of the donor (Dewi & Tauris 2000; Xu & Li 2010; Loveridge et al. 2011; Klencki et al. 2021; Marchant et al. 2021). While some authors use a constant value of λ (typically 0.5 or 1.0), others calculate it based on the binding energy of the envelope and structure of the star. However, these calculations are plagued by uncertainties related to the energies that should be considered to calculate the binding energy.

In our calculations, we adopted different efficiencies (α ranging from 0.1 to 0.9, in steps of 0.1). The envelope-structure parameter λ was calculated according to a similar fitting scheme as provided by Claeys et al. (2014, their Appendix A), which is based on the detailed numerical stellar evolution calculations by Dewi & Tauris (2000) and takes into account the structure and the evolutionary stage of the red giant donor and the envelope thermal energy as constrained by the virial theorem (i.e. increasing λ by a factor of two).

We assumed solar metallicity (i.e. $Z = 0.02$) and a constant star formation rate (e.g. Weidner et al. 2004; Kroupa et al. 2013; Recchi & Kroupa 2015; Schulz et al. 2015) over the age of the Galactic disc ($\approx$ 10 Gyr, Kilic et al. 2017). Unless clearly mentioned, we used the standard BSE values for all other stellar and binary evolution parameters (e.g. Hurley et al. 2002; Belloni et al. 2018; Banerjee et al. 2020).

After a post-CE binary is formed, it evolves towards shorter orbital periods through orbital angular momentum loss. We included magnetic braking and emission of gravitational waves as mechanisms to remove orbital angular momentum as described in Hurley et al. (2002, section 2.4, equation 48). Regarding magnetic braking, we adopted the saturated and disrupted magnetic braking prescription with the scaling factors inferred by Belloni et al. (2024a).

4. Results and Discussion

4.1. Properties of Post-CE Binaries

We start our presentation of the predicted post-CE binary populations by inspecting the WD mass versus orbital period plane. We compare in Fig. 1 the observed properties of the detached post-CE binaries hosting AFGK-type main-sequence stars with the predicted in our population synthesis, as a function of α. We also included in Fig. 1 the maximum post-CE orbital period for specific zero-age companion masses, namely 0.5, 1.0 and 1.5 $M_\odot$. As expected, the higher the efficiency, the longer the maximum post-CE orbital period, because the orbital energy is used more efficiently to unbind the CE for higher values of α, resulting in less orbital shrinkage.

Although not shown in the figure, for extremely low-efficiency CE evolution ($\alpha \lesssim 0.1$), post-CE orbital periods are shorter than $\sim$ 50 days. The lower the WD mass, the shorter the predicted post-CE orbital periods. Interestingly, post-CE binaries hosting WDs with masses lower than ~ 0.5 $M_\odot$ are virtually not predicted at all when CE evolution is highly inefficient. Such post-CE binaries would need to form when the WD progenitor is on the FGB, which means that in most cases the onset of the CE evolution occurs at a relatively short orbital separation. Therefore, if α is small, there is not enough orbital energy available to successfully unbind the CE, resulting in a merger.

On the other hand, for highly efficient CE evolution ($\alpha \gtrsim 0.9$), post-CE orbital periods can be as long as a few hundred days, for low-mass carbon-oxygen WDs, and a thousand days, for oxygen-neon WDs. The post-CE binaries with the longest orbital periods typically descend from pre-CE binaries with orbital periods longer than 10^4 d, having TP-AGB donors with large radii ($\gtrsim 1400$ $R_\odot$) and tiny envelopes ($\lesssim 0.5$ $M_\odot$).

We further predict an accumulation of systems at shorter orbital periods (between $\sim 1 - 10$ d) for WDs more massive than ~ 0.9 $M_\odot$, which is always present regardless of α, but which becomes more pronounced when α increases. This accumulation is a consequence of the stellar type of the WD progenitor at the onset of the CE evolution. For those systems, CE evolution occurred when the WD progenitor was still ascending the AGB or just became a TP-AGB star. For all systems with longer orbital periods (i.e. above these accumulations in Fig.1), the onset of the CE evolution occurred when the donor was already an evolved TP-AGB star, with a less massive and less bound envelope.

When compared to the observational sample of long-period post-CE binaries hosting oxygen-neon WDs and AFGK-type main-sequence stars, we can conclude that their properties can be explained for any CE efficiency $\alpha \gtrsim 0.2$. For efficiencies lower than that, the predicted maximum post-CE orbital period is typically shorter than those of observed systems. Given that the location of the observed systems is above the accumulation of post-CE binaries with massive WDs and short orbital periods we mentioned earlier, these systems must descend from systems where the CE evolution started when the donor star was an evolved TP-AGB star. We show later that this is indeed the case.

Although our focus here is on post-CE binaries containing oxygen-neon WDs, we note that our simulations predict plenty of long-period systems with carbon-oxygen WDs, which is consistent with observations. For instance, the self-lensing post-CE binary KOI 3278 harbours a carbon-oxygen WD with a G-type main-sequence star and has an orbital period of $\approx$ 88 d (Kruse & Agol 2014; Yahalomi et al. 2019). More recently, Garbutt et al. (2024) and Yamaguchi et al. (2024b) found a sizeable sample of long-period post-CE binaries hosting WDs with masses $\sim 0.6 - 0.9$ $M_\odot$. We plan to address the evolutionary history of these systems in the future.

4.2. Formation Pathways

We have just shown that post-CE binaries hosting oxygen-neon WDs can have orbital periods from several tens of days (for $\alpha \sim 0.1$) up to a thousand days (for $\alpha \sim 1.0$), without including energy sources other than orbital, gravitational and thermal in the CE energy budget. We now turn our discussion to the specific formation pathways of the six known post-CE binaries we have been discussing. We were able to successfully find very decent models for each of the six observed post-CE binaries. Examples of formation pathways for each one of them can be found in Tabs. A.1–A.6 in Belloni et al. (2024b).

We searched for best-fitting models using the BSE code by carrying out pre-CE and CE evolution adopting the assumptions described in Sect. 3 and assuming that the zero-age main-sequence binary orbit was circular. We set the CE efficiency to $\alpha = 0.3$, which is consistent with the increasing evidence that short-period post-CE binary progenitors experience strong orbital shrinkage during CE evolution (e.g. Zorotovic et al. 2010; Toonen & Nelemans 2013; Camacho et al. 2014; Cojocaru et al. 2017; Belloni et al. 2019; Hernandez et al. 2022; Zorotovic & Schreiber 2022; Scherbak & Fuller 2023). For each observed system, we ran a large grid of binary models varying the zero-age mass of the WD progenitor from 6 to 8 $M_\odot$, in steps of 0.01 $M_\odot$ and the zero-age orbital period from 10^3 to 10^4 d, in steps of 5 d. And, finally, the zero-age mass of the companion was chosen to be slightly smaller than the observed values as it increases during binary evolution due to wind accretion. After finding within the grid the model closest to the observed one, we made the grid finer around this model to finally obtain a best-fitting model. We should emphasize that the models provided in Tabs. A.1–A.6 in Belloni et al. (2024b) are not the only best-fitting model. Instead, each one of them belongs to a family of solutions able to explain the observed system, this family arises from varying other assumptions such as zero-age eccentricity, stability of mass transfer, wind accretion efficiency/model, metallicity, among others.

Despite that, these families of models share the same fundamental features, which characterize the formation pathways of long-period post-CE binaries hosting oxygen-neon WDs and AFGK-type main-sequence stars. As these systems host oxygen-neon WDs, for solar metallicity and the assumptions within the BSE code for stellar evolution, the initial mass of their progenitors must have been $\gtrsim 6$ $M_\odot$. Such stars lose only a negligible amount of mass before becoming a TP-AGB star. This means that they start the TP-AGB phase with a very massive

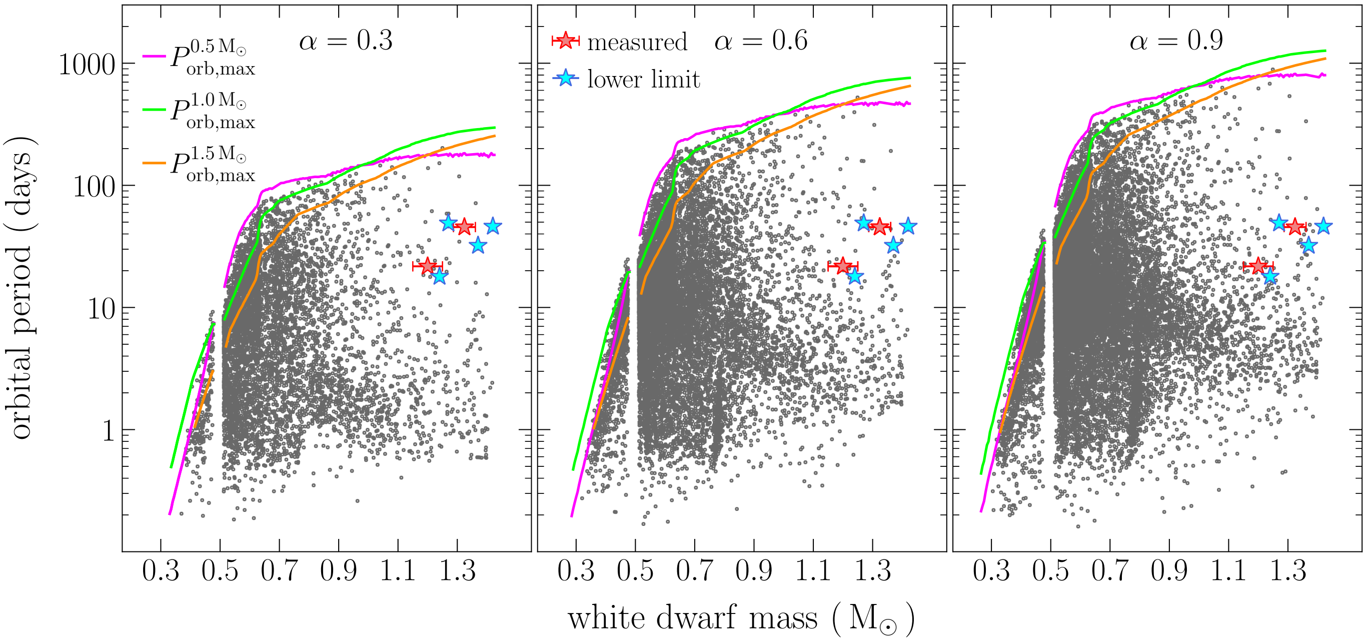

Figure 1. Distribution of present-day detached post-CE binaries with main-sequence stars of spectral type earlier than M (i.e. masses greater than 0.5 $M_\odot$) in the plane WD mass versus orbital period (black circle points), each panel corresponding to a different choice of the CE efficiency α, namely 0.3 (left panel), 0.6 (middle panel), and 0.9 (right panel). We also included in each panel the maximum orbital period as a function of the WD mass, for zero-age companion masses of 0.5 $M_\odot$ (magenta line), 1.0 $M_\odot$ (green line), and 1.5 $M_\odot$ (orange line). On top of that, we included the six known long-period post-CE binaries with oxygen-neon WDs, two of them (red stars) having measured WD masses and four of them having only lower limits for the WD mass (blue stars). In all simulations, no extra energy source besides the orbital, the gravitational and the thermal was adopted in the CE energy budget. All known systems can be easily explained assuming $\alpha \gtrsim 0.2$. In addition, for a given WD mass, the greater α, the longer the maximum orbital period. For $\alpha \sim 1$, even post-CE binaries with orbital periods as long as a thousand days can be explained.

and strongly bound envelope. In the case they fill their Roche lobe with a large envelope mass fraction, the resulting post-CE orbital period will be necessarily much shorter than those observed among these six known systems.

In all cases, to reproduce the observed long orbital periods, two main conditions at the onset of the CE evolution are required. First, the WD progenitor has to fill its Roche lobe being a highly evolved TP-AGB star (i.e. when more than 50% of its mass has already been lost through stellar winds), resulting in an envelope-structure parameter of $\sim 1.0 - 1.2$. Second, the orbital period has to be several thousand days. This is because highly evolved TP-AGB stars can develop more loosely bound envelopes, and fill their Roche lobes at sufficiently long orbital periods so that the fraction of the available orbital energy that is required to eject the envelope does not lead to a strong orbital shrinkage. Otherwise, the resulting post-CE binary would have a much shorter orbital period.

Most importantly, unlike what has been claimed for a long time, no extra energy is required to explain the well-known system IK Peg and the six recently discovered systems. Therefore, our results provide further support for inefficient CE evolution as the most common formation channel of post-CE binaries hosting WDs, regardless of whether they have short or long orbital periods.

4.3. Comparison with Previous Works

The discussion concerning possible contributions of the ionization/recombination energy to the ejection of planetary nebulae during single star evolution started in the sixties (e.g. Paczyński & Ziółkowski 1968). In the nineties, Han et al. (1994) and Han et al. (1995) further investigated the importance of the ionization energy of hydrogen and helium to the internal energy of the envelopes not only of single stars but also in stars undergoing CE evolution. Whether recombination energy can have a significant impact on the CE ejection or not has since then been an active topic of research (e.g. Ivanova et al. 2013; Röpke & De Marco 2023, and references therein).

To the best of our knowledge, Davis et al. (2010) was the first to claim that extra energy is required to explain the properties of IK Peg, which was the only long-period post-CE binary hosting an oxygen-neon WD known before Gaia DR3. They carried out post-CE population synthesis adopting a similar scheme to ours to calculate their envelope-structure parameters, that is, based on the detailed calculations performed by Dewi & Tauris (2000), although these authors interpolated the tabulated values provided by Dewi & Tauris (2000) and extended their grid with the same code. They also used a set of 5.4×10^5 zero-age main sequence binaries, which is a number comparable to ours.

In our post-CE binary population synthesis, whose results are illustrated in Fig. 1, we predict the existence of long-period post-CE binaries similar to the six systems we address here. It is not clear to us why Davis et al. (2010) failed to predict the existence of such systems. The disagreement might be related to ambiguity in several terms used by Davis et al. (2010). For instance, it is difficult to understand what they call 'thermal energy', 'internal energy', 'recombination energy', 'ionization energy', and 'extra energy'. Because of this problem, discussing in more detail differences of our results to those obtained by Davis et al. (2010) appears to be a rather futile exercise.

In the same year, Zorotovic et al. (2010) also claimed that IK Peg needed extra energy sources, based on a similar approach to the one used by Davis et al. (2010). However, as stated in Zorotovic et al. (2010), they required the progenitors to have a luminosity lower than the peak luminosity of the first thermal pulse. Therefore, potential progenitors during the subsequent pulses were not considered. The limits derived by Zorotovic et al. (2010) correspond to shorter orbital periods (much shorter than the observed systems discussed in this work). This is not surprising as we have shown in the previous sections that evolved TP-AGB donors are required to reproduce the observed systems. However, eliminating the condition that the progenitor luminosity should be lower than the peak luminosity of the first thermal pulse from the algorithm developed by Zorotovic et al. (2010), the maximum post-CE orbital periods we calculated here with the BSE code and those computed with their method agree reasonably well (see Belloni et al. 2024b, for details).

Most recently, Yamaguchi et al. (2024a) claimed that highly efficient CE evolution, with the inclusion of a significant fraction of recombination energy, is needed to explain the five long-period binaries from *Gaia* DR3 containing oxygen-neon WDs they discovered (and which we addressed in this work). One clear aspect of the formation pathways we found here is that the WD progenitors have to be highly evolved TP-AGB stars at the onset of the CE evolution. This means that the red giant had enough time to lose a significant fraction of its mass ($\gtrsim 50\%$) before filling its Roche lobe. Yamaguchi et al. (2024a) used the MESA code to evolve a 7 $M_{\odot}$ pre-main-sequence star up to the AGB. In other words, these authors did not follow the evolution of the star during the TP-AGB phase as they stopped their simulation before carbon ignition, when the star was not as big as it could get and had lost virtually no mass through stellar winds. This is most likely the reason why Yamaguchi et al. (2024a) needed to include recombination energy and to assume highly efficient CE evolution in their calculations to reproduce the five systems and IK Peg.

5. Conclusions

We carried out post-CE binary population model with the BSE code aiming to inspect whether energy sources other than orbital, gravitational and thermal should be included in the CE evolution energy budget to reproduce the six known long-period post-CE binaries with oxygen-neon WDs and AFGK-type main-sequence stars. We found that all six systems can be reproduced reasonably well with inefficient CE evolution without invoking extra energy. This was achieved by allowing the WD progenitors to become highly evolved TP-AGB stars before filling its Roche lobe, at the onset of the CE evolution. We also found that post-CE binaries can have orbital periods as long as a thousand days when all available orbital energy is used to unbind the CE. Our results, published in Belloni et al. (2024b), provide further evidence for a common origin of post-CE binaries with WD primaries, that is, it seems all observed systems are consistent with having formed through inefficient CE evolution, irrespective of their post-CE orbital period.

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