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The formation of the self-lensing binary KOI 3278

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Abstract. For decades, observed long-period post-common-envelope (CE) binaries have been interpreted as evidence for additional energies to contribute during CE evolution. Belloni et al. have recently shown that this argument is based on simplified assumptions for all long-period post-CE binaries containing massive white dwarfs (WDs). The only remaining post-CE binary that has been claimed to require contributions from additional energy sources to understand its formation is KOI 3278. Here, we address in detail the potential evolutionary history of KOI 3278. In particular, we investigated with the MESA code whether extra energy sources, such as recombination energy, are indeed required to explain its existence. We found that KOI 3278 can be explained if the WD progenitor filled its Roche lobe during a helium shell flash and recombination energy is not required. We conclude that currently not a single observed post-CE binary requires to assume energy sources other than gravitational and thermodynamic energy to contribute to CE evolution. KOI 3278, however, remains an intriguing post-CE binary as, unlike its siblings, understanding its existence requires highly efficient CE ejection.

Resumo. Por décadas, binárias pós-envelope-comum de longo período foram interpretadas como evidência de energias adicionais que contribuem durante a evolução de envelope comum. Belloni et al. mostraram recentemente que esse argumento é baseado em suposições simplificadas para todas as binárias pós-envelope-comum de longo período contendo anãs brancas massivas (WDs). A única binária pós-envelope-comum restante que foi reivindicada como exigindo contribuições de fontes de energia adicionais para entender sua formação é KOI 3278. Aqui, abordamos em detalhes a potencial história evolutiva de KOI 3278. Em particular, investigamos com o código MESA se fontes extras de energia, como energia de recombinação, são de fato necessárias para explicar sua existência. Descobrimos que KOI 3278 pode ser explicada se a progenitora da WD preencheu seu lóbulo de Roche durante um flash da camada de hélio e energia de recombinação não é necessária. Concluímos que atualmente nenhuma binária pós-envelope-comum observada requer assumir fontes de energia diferentes de energia gravitacional e termodinâmica para contribuir para a evolução de envelope comum. KOI 3278, no entanto, continua sendo uma binária pós-envelope-comum intrigante, pois, diferentemente de suas irmãs, entender sua existência requer uma ejeção de envelope comum altamente eficiente.

Keywords. stars: AGB and post-AGB – binaries: general – methods: numerical – stars: evolution – stars: individual: KOI 3278 – white dwarfs

1. Introduction

For the vast majority of observed post-common-envelope (CE) systems hosting white dwarfs (WDs), with typical orbital periods of hours to a few days, it has been found that inefficient CE evolution, only taking into account thermal and gravitational energies, convincingly explains the observations. However, two types of post-CE binaries have challenged this picture, namely, the Kepler Object of Interest 3278 (KOI 3278) and long-period systems with oxygen-neon WDs. These two types of systems have been claimed to require contributions of additional energy sources, such as recombination energy, during CE evolution to explain their current characteristics, in particular their long orbital periods.

We have recently shown that there is no need to invoke extra energy sources to explain the long orbital period post-CE binaries with oxygen-neon WDs if CE evolution was triggered by dynamically unstable mass transfer from a highly evolved thermally pulsing asymptotic giant branch (TP-AGB) star (Belloni et al. 2024b). In this case, at the onset of mass transfer, the mass of the envelope of the donor is comparable to the mass of its core, which means the envelope is sufficiently loosely bound and can be ejected due to the input of relatively little orbital energy, resulting in a long-period post-CE binary with a massive WD. The single remaining system that has been claimed to provide evidence for contributions from additional energy sources is thus KOI 3278.

In this work, we investigated whether a formation pathway that includes detailed calculations of the TP-AGB phase can not only explain the existence of the long period post-CE binaries containing oxygen-neon WDs (Belloni et al. 2024b), but also the properties of KOI 3278 which contains a WD of much lower mass, without additional energy sources. We carried out binary models with the MESA[1] code (Jermyn et al. 2023, and references therein). We found that for post-CE binaries with low-mass carbon-oxygen WDs ($\lesssim 0.55\ M_\odot$) and sufficiently long orbital periods, like KOI 3278, the onset of CE evolution has to occur during a helium shell flash, when the WD progenitor is at the beginning of the TP-AGB phase, to explain their current orbital periods without considering energy sources in addition to orbital and thermodynamic internal energy. Here, we present a summary of this work, which was published in Belloni, Schreiber, & Zorotovic (2024a).

2. Formation Pathway for KOI 3278

We found that a binary with zero-age main-sequence masses of ~ 1.5 and $\sim 0.9\ M_\odot$ and orbital period of ~ 920 d, evolves to

[1] For reference, interested readers can access the MESA files that we made available at https://zenodo.org/records/10841636.

Table 1. Main predicted (Belloni, Schreiber, & Zorotovic 2024a) and observed (Yahalomi et al. 2019) parameters of KOI 3278.

Parameter	Observed	Predicted
orbital period (d)	88.1805	88.1805
WD mass ($M_\odot$)	$0.5250^{+0.0082}_{-0.0089}$	0.531
main-sequence companion		
mass ($M_\odot$)	$0.911^{+0.023}_{-0.026}$	0.910
radius ($R_\odot$)	$0.861^{+0.028}_{-0.023}$	0.861
$T_{\rm eff}$ (K)	5384^{+45}_{-44}	5385
$\log\,g$ (cm s^{-2})	$4.525^{+0.028}_{-0.035}$	4.527
age (Gyr)	$4.3^{+3.2}_{-2.6}$	5.2
metallicity	[Fe/H] = 0.118 ± 0.040	Z = 0.024

the required initial post-CE binary to explain KOI 3278. When the WD progenitor becomes an evolved first giant branch star, wind accretion is no longer negligible and the companion mass slightly increases. As soon as the WD progenitor becomes a TP-AGB star, it fills its Roche during the first helium shell flash, when its mass is ≈ 1.18 $M_\odot$ and its hydrogen-free core has a mass of ≈ 0.53 $M_\odot$. At this moment, the orbital period is ≈ 978 d and the companion mass increased to ≈ 0.91 $M_\odot$ due to wind accretion. The observed orbital period of ≈ 88 d can be reproduced if a fraction of ≈ 0.97 of the change in the orbital energy is used to unbind the CE. Afterwards, when the post-CE binary is ≈ 2.2 Gyr old and the main-sequence companion is ≈ 5.2 Gyr old, the properties of the main-sequence star resemble the observed ones.

We show in Fig. 1 the pre- and post-CE evolution of the radius of the main-sequence companion as a function of its effective temperature. For the post-CE evolution, the different colours indicate its $\log g$. During pre-CE evolution, both the effective temperature and the radius of the main-sequence companion initially increased. This trend is reversed due to the accretion of a fraction of the stellar winds from the WD progenitor for a short period of time. After ≈ 2.2 Gyr of post-CE evolution, the properties of the main-sequence companion are quite similar to those of the G-type star in KOI 3278. The properties we predict in our modelling with MESA are compared with the observed in Tab 1.

3. Conclusions

We have recently shown that long orbital period post-CE binaries containing massive oxygen-neon WDs can form through CE evolution without assuming extremely efficient CE evolution and without assuming that additional energy sources contribute to expelling the envelope. This exercise left KOI 3278 as the only observed post-CE binary that has been claimed to provide evidence for contributions from additional energy sources such as recombination energy. We carried out binary evolution simulations with the MESA code showing that the existence of KOI 3278 can be explained if the WD progenitor fills its Roche lobe during a helium shell flash occurring with the first thermal pulses on the AGB and that in this case, the available gravitational and thermodynamic energy are sufficient to expel the envelope. Our results, published in Belloni, Schreiber, & Zorotovic (2024a), have two fundamentally important implications for understanding CE evolution. First, incorporating the detailed evolution of the early and late AGB in reconstructing CE evolution is fundamental to avoid drawing wrong conclusions. Second, given our result on KOI 3278, not a single post-CE binary consisting of a WD with a stellar companion provides evidence for additional energy sources such as recombination energy to play a role during CE evolution. Nevertheless, KOI 3278 remains an intriguing system. In contrast to the vast majority of observed post-CE binaries, understanding the existence of KOI 3278 requires assuming that nearly all the available orbital energy is used to unbind the CE.

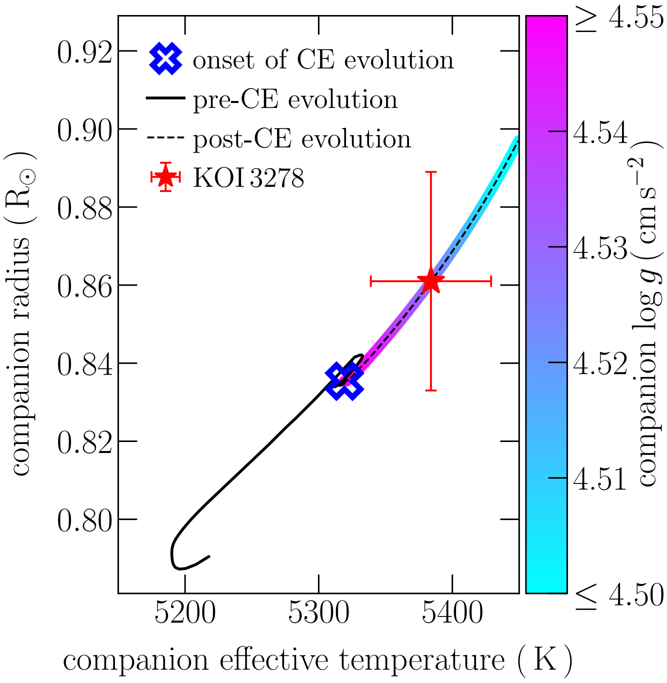

Figure 1. Evolution of the main-sequence companion radius with its effective temperature. The black line corresponds to the pre-CE evolution, while the dashed line represents the post-CE evolution. The colours indicate its $\log g$ during post-CE evolution. The blue marker indicates the onset of the CE evolution and the red star the observed properties. During pre-CE evolution, the effective temperature and radius increase but this is reversed due to accretion of a portion of the stellar winds of the WD progenitor. After ≈ 2.2 Gyr of post-CE evolution, the main-sequence companion has properties that are similar to those of the G-type star in KOI 3278.

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