WD 1856 b: a close giant planet around a white dwarf that could have survived a common-envelope phase

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ABSTRACT

The discovery of a giant planet candidate orbiting the white dwarf WD 1856+534 with an orbital period of 1.4 d poses the questions of how the planet reached its current position. We here reconstruct the evolutionary history of the system assuming common envelope evolution as the main mechanism that brought the planet to its current position. We find that common envelope evolution can explain the present configuration if it was initiated when the host star was on the AGB, the separation of the planet at the onset of mass transfer was in the range 1.69–2.35 au, and if in addition to the orbital energy of the surviving planet either recombination energy stored in the envelope or another source of additional energy contributed to expelling the envelope. We also discuss the evolution of the planet prior to and following common envelope evolution. Finally, we find that if the system formed through common envelope evolution, its total age is in agreement with its membership to the Galactic thin disc. We therefore conclude that common envelope evolution is at least as likely as alternative formation scenarios previously suggested such as planet-planet scattering or Kozai-Lidov oscillations.

Key words: binaries: close – planet-star interactions – white dwarf

1 INTRODUCTION

The vast majority of the stars in the Galaxy, including our Sun and virtually all known planet hosts will end their lives as white dwarfs. It is now well established that planets can survive the transformation of their host star into a white dwarf (Villaver & Livio 2007; Mustill & Villaver 2012; Rao et al. 2018; Ronco et al. 2020). Indirect observational evidence for the existence of planets around white dwarfs comes from the detection of photospheric metal absorption lines found in 20 – 30 per cent of all white dwarfs (Zuckerman et al. 2010; Koester et al. 2014; Hollands et al. 2017), the discovery of dusty (Zuckerman & Becklin 1987; Farihi et al. 2009; Rocchetto et al. 2015; Wilson et al. 2019) and gaseous discs (Gänsicke et al. 2006, 2007; Dennihy et al. 2020; Melis et al. 2020) around a small sub-sample of these white dwarfs, the detection of a transiting planetesimal (Vanderburg et al. 2015) in the process of disintegration (Gänsicke et al. 2016), orbital motion in the gaseous disc around the white dwarf SDSSJ1228+1040 which potentially indicates the presence of a planetary remnant (Manser et al. 2019), and finally an evaporating giant planet in close orbit around the young and hot white dwarf WD J0914+1914 (Gänsicke et al. 2019). In all the above cases, the planetary material in close orbit around the white dwarf is usually assumed to have been scattered inward by gravitational interactions with a larger body, most likely a massive gas giant planet (Mustill et al. 2018).

Very recently, Vanderburg et al. (2020) reported the discovery of a giant planet candidate, WD 1856 b, orbiting the cool and old white dwarf WD 1856+534 (hereafter WD 1856) with a short orbital period (> 1.4 d). The authors discussed several evolutionary scenarios that could in principle explain the close orbit of the massive planet (> 10 – 15 Mjup), including common envelope (CE) evolution, dynamical instability in a multiplanet system through the Kozai-Lidov (KL) mechanism (the white dwarf belongs to a visual triple star system) or planet-planet scattering events, both followed by tidal circularization, as well as other less likely scenarios such as instabilities due to galactic tides, close stellar encounters, close encounter scattering events between two planets near the periastron, tidal dissipation during the stellar giant phase, and partial tidal disruption. In line with the generally accepted interpretation for planetesimals and even Neptune-mass planets found in the proximity of white dwarfs, Vanderburg et al. (2020) concluded that dynamical instabilities through close encounters with an additional object in the system, which excited large orbital eccentricities and subsequent tidal circularization, is the most reasonable explanation for the close orbit of WD 1856 b.

Here we take a closer look at one scenario that has been considered unlikely by Vanderburg et al. (2020), i.e. CE evolution. We
reconstruct the CE phase following the evolution of the progenitor of the white dwarf and find that CE evolution is in fact a plausible scenario to explain the current orbital configuration of the system. As in several close binary systems that most likely formed through CE evolution, only a small fraction of recombination energy is required to contribute to the envelope ejection process.

2 REVIEWING THE ARGUMENTS AGAINST COMMON ENVELOPE EVOLUTION

Vanderburg et al. (2020) concluded that a CE evolution was highly unlikely to be the origin of the planet’s current proximity to the white dwarf based on two arguments. The authors highlighted that the known white dwarf (and subdwarf) plus brown dwarf binaries collated by Nelson et al. (2018) differ from WD 1856 as all have short (≤4 h) orbital periods and large (≥50 Mₐ₉) masses, i.e. rather different from the much longer period and lower mass of the planet candidate in WD 1856, providing an empirical argument that it might not have survived CE evolution. However, the sample listed by Nelson et al. (2018) is small, and likely subject to significant selection effects. The majority of these systems were identified via the detection of either eclipses (Geier et al. 2011) or emission lines from the irradiated companion (Maxted et al. 2006). Companions with longer orbital periods have a rapidly dropping probability of eclipsing the white dwarf, and their surfaces intercept less flux from the white dwarf resulting in weaker or absent emission lines. The latter is of course also true for companions orbiting cooler white dwarfs. We note here that GD 1400 is a nearby (∼46 pc) white dwarf with a long-period (≈10 h, Burleigh et al. 2011) brown dwarf companion identified initially as a weak infrared excess (Farihi & Christopher 2004).

The much larger sample of post CE binary stars with low-mass stellar companions spans a wider range of orbital periods and both CE efficiencies as well as the contributions from additional energy sources required to reconstruct their evolutionary paths can vary (Nebot Gómez-Morán et al. 2011; Zorotovic et al. 2014). The longer period of WD 1856 b might therefore, on its own, not represent a strong argument against CE evolution.

Vanderburg et al. (2020) also performed a simple reconstruction of CE evolution based on an analytic study of the parameterized equation that relates the binding energy of the envelope and the change in orbital energy:

$$\frac{GM_1 M_2}{\lambda R_L} = \alpha_{CE} \left( \frac{GM_1 M_2}{2a_1} - \frac{GM_1 M_2}{2a_i} \right)$$

(1)

where $M_1$, $M_2$, $\lambda$, and $a_i$ are the masses of the primary star (the white dwarf progenitor), its envelope, its core (the future white dwarf) and the companion (the planet candidate), respectively, at the onset of CE evolution. $R_L$ and $a_i$ are the Roche lobe of the primary star and the orbital separation when the Roche lobe is filled, and $a_i$ is the orbital separation immediately after the CE is ejected. The CE efficiency, $\alpha_{CE}$, corresponds to the fraction of orbital energy lost during the CE phase that is used to unbind the envelope of the white dwarf progenitor, while $\lambda$ is a binding energy parameter that depends on the mass and evolutionary stage of the giant star. Vanderburg et al. (2020) neglected the second term in the right-hand side of Eq. 1 and used an analytical expression for the maximum radius of the star that only depends on its core mass (Eq. 8 in their article). Using those assumptions, they derived the orbital period at the onset of the CE phase which combined with Eq. 1 translates into an expression for the minimum $\alpha_{CE} \lambda$ needed to unbind the envelope (avoiding a merger) that only depends on the measured parameters (white dwarf mass, companion mass and orbital period) and on the mass of the white dwarf progenitor. Vanderburg et al. (2020) found that the values of $\alpha_{CE} \lambda$ they derived were larger than the tabulated results of Xu & Li (2010), which were computed for different progenitor masses and for a range of typical radii, even when including recombination energy, and concluded that CE evolution is a highly unlikely scenario. However, a caveat to that conclusion is that the resolution in stellar mass of the tables from Xu & Li (2010) is very coarse (1 M⊙), and that these authors did not consider mass loss prior to the envelope ejection.

Here we therefore perform a more detailed reconstruction of the CE phase, considering mass loss prior to this phase, the possible contribution of recombination energy to the process of ejection of the envelope, and proper calculations for $\lambda$ depending on the mass and the evolutionary state of the primary star.

3 RECONSTRUCTING COMMON ENVELOPE EVOLUTION

Based on its kinematics, Vanderburg et al. (2020) found that WD 1856 most likely belongs to the thin disc of the Galaxy, which puts an upper limit of ≈10 Gyr on the age of the system. As already noted by Vanderburg et al. (2020), if the white dwarf formed from single star evolution, this age limit is in conflict with the best-fit white dwarf mass (0.518 ± 0.055 M⊙), i.e. the sum of the white dwarf cooling age and the main-sequence life time of its progenitor exceed the age of the thin disc.

We revisit this problem by calculating the total age of WD 1856 using the single star evolution (SSE) code (Hurley et al. 2000) for the main sequence and post main sequence evolution and the white dwarf models of Bédard et al. (2020) to determine the cooling age of the white dwarf. Given the atmosphere of WD 1856 is most likely a mixture of hydrogen and helium (Vanderburg et al. 2020), we computed the age for the two limiting cases, where, for a given mass, the pure hydrogen and pure helium case represent an upper and lower limit on the cooling age of the white dwarf. The total age of WD 1856, if formed through single star evolution, is illustrated by the blue dashed line in Fig. 1, clearly indicating that the white dwarf mass has to be ≥0.57 M⊙ for its age to be below 10 Gyr, with the exact value depending on the uncertain atmosphere composition. If the white dwarf mass is as small as measured by Vanderburg et al. (2020), every evolutionary scenario for WD 1856 and its close-in planet that assumes the white dwarf has formed through single star evolution, implies an age of the white dwarf in conflict with its membership to the thin disk of the Galaxy. CE evolution can truncate the core-growth of a giant star and therefore more massive stars, with a shorter main sequence lifetime, can be the progenitors of low-mass white dwarfs, which reduces the total age of the system.

To evaluate the possibility of CE evolution for WD 1856 we here use an algorithm that we previously applied to reconstruct CE evolution of white dwarfs with close low-mass star companions (Zorotovic et al. 2010, 2014). In brief, the algorithms works as follows. We calculated a grid of stellar evolution tracks using SSE with initial masses up to eight solar masses (with a step size of 0.01 M⊙). As CE evolution truncates the core growth of the giant star, the core mass of the giant star at the onset of CE evolution must have been equal to the
white dwarf mass in the post-CE system. We therefore first search our grid for giant stars with a core mass equal to the measured white dwarf mass. As we know the radius and the mass of each of the identified potential white dwarf progenitor stars, we can for all of them determine the orbital period at the onset of CE evolution using the mass of the companion and Roche-geometry. In other words, we can determine the period and stellar masses for every possible progenitor system. Knowing the stellar masses and the period at the onset of CE evolution and comparing it with those of the post-CE system, provides the change in orbital energy during CE evolution for each of these potential progenitor binary star systems. As we also know the amount of recombination energy stored in the envelope of the giant at the onset of CE evolution, computed with the binary star evolution (BSE) code (Hurley et al. 2002; Claeys et al. 2014), we can test whether sufficient energy is available to unbind the envelope of the giant. If this is the case, we consider this particular system a possible progenitor configuration. Searching our finely spaced grid, we can therefore find virtually all possible progenitors for a given white dwarf mass, post-CE orbital period, and companion mass. If the effective temperature of the white dwarf is known as well, we can also calculate the total age of each potential progenitor system by summing the cooling age of the white dwarf (obtained from the tracks of Bédard et al. 2020) as well as the main sequence and post main sequence lifetime of the progenitor star (obtained from SSE).

We searched for CE progenitor configurations for WD 1856 over a range of white dwarf masses covering twice the uncertainty in mass provided by Vanderburg et al. (2020), i.e. $0.408 - 0.628 M_\odot$. We used the measured current orbital period of 1.41 d, and adopted a mass of 14 $M_{\text{jup}}$ for the planet, which corresponds to the upper end of the mass range derived by Vanderburg et al. (2020), and again the two limiting cases for the composition of the atmosphere (pure hydrogen and pure helium). The shaded regions in Fig. 1 show the possible progenitor systems that we identified as a function of total age and white dwarf mass. We distinguish three cases for the contribution of recombination energy to unbind the CE: no recombination energy used (i.e. $\alpha_{\text{rec}} = 0$, black area), less than 10 per cent of contribution (i.e. $0 < \alpha_{\text{rec}} \leq 0.1$, solid gray area), and up to 100 per cent of contribution (i.e. $0 < \alpha_{\text{rec}} \leq 1$, shaded gray area). The vertical line shows the best-fit white dwarf mass of Vanderburg et al. (2020), and the two lower and upper horizontal red lines give the estimated age for the thin disc of the Galaxy and the Hubble time, respectively.

To what degree recombination energy can contribute to CE ejection is intensively discussed. While Ivanova et al. (2015) suggest that recombination energy can play a fundamental role, others (e.g. Soker & Harpaz 2003) argue that the opacity of the envelope is too small for recombination energy to provide an important contribution. Based on the latter argument and on the fact that the evolutionary history of two post-CE binary star systems with long orbital periods (IK Peg and KOI-3278) can be understood by assuming a small fraction (1 and 2 per cent) of recombination energy to contribute (Zorotovic et al. 2010, 2014), we here consider as realistic those cases in which the efficiency of recombination energy remains below 10 per cent. Table 1 lists the orbital parameters, initial and at the onset of CE evolution, for the possible solutions, taking into account the restriction in age and keeping the fraction of recombination energy below 10 per cent (dark grey and black regions in Fig. 1).

In all the reconstructed cases within these two constraints, the progenitor had to be on the thermally pulsating asymptotic giant branch (TPAGB) phase when it filled its Roche lobe. During this phase the binding energy parameter $\lambda$ can take values well above unity when recombination energy is considered (see Fig. 5 in Camacho et al. 2014), which implies that the envelope can be very loosely bound. Therefore, even considering only a small fraction of the available recombination energy to contribute to the ejection process allows us to reconcile the current configuration of the white dwarf and the surrounding planet candidate with CE evolution. Also, according to our reconstruction code, the progenitor of the white dwarf must have already lost $\approx 20$ per cent of its initial mass when the CE phase occurred, which facilitates the ejection.

The large number of possible solutions we find with our recon-
construction algorithm clearly illustrates that CE evolution represents a plausible scenario for the formation of WD1856 and its close planetary companion. In particular, CE evolution allows for a larger range of masses and younger ages for the white dwarf than formation scenarios that assume the white dwarf formed through single star evolution.

4 PRIOR TO COMMON ENVELOPE EVOLUTION

In order to trigger CE evolution, the planet WD 1856 b must have been located at $1.69 - 2.35$ au at the end of the main sequence evolution of its host star. This separation can be achieved early during the pre-main sequence due to angular momentum exchange between the planet and the protoplanetary disc. The classical core accretion formation scenario (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996), along with type I and II disc migration (Ward 1997; Tanaka et al. 2002; Lin & Papaloizou 1986; Armitage 2007), can naturally lead to formation of planets like WD 1856 b at locations in the range of $\sim 1 - 10$ au (see Mordasini 2018, for details). Furthermore, even planets formed through gravitational instability can be subject to disc migration (Boss 2005; Cha & Nayakshin 2011). In particular, with 2D hydrodynamical simulations Baruteau et al. (2011) showed that these planets can migrate inward due to their interactions with the disc on the fast type I migration-like time-scales.

Given that WD 1856 and its planetary companion are members of a multiple star system, with a distant M-dwarf binary, an alternative evolution of the system prior to CE evolution are KL oscillations (Kozai 1962; Lidov 1962). In order to evaluate this possibility, we used the SECULARMULTIPLE code (Hamers & Portegies Zwart 2018, 2020), which allows to calculate the secular orbit-averaged evolution of the planet during the main sequence evolution of the host star, including the effect of tidal bulges, tidal friction and general relativity. We also implement the single-star-evolution (SSE) code (Hurley et al. 2000) to model radial expansion, contraction, structure changes, and mass loss due to stellar evolution of the white dwarf progenitor. We found that for the case of 1.41 and 2.31 $M_\odot$ white dwarf progenitor masses and initial semi-major axis exceeding 4 au, the star can experience Roche lobe overflow during the asymptotic giant branch as required to trigger CE evolution. While the exact outcome of the quadruple dynamics is very sensitive on the initial values of the argument of periastris, longitude of ascending nodes, and eccentricity of the outer binary, and in particular the mutual inclination, this shows that quadruple dynamics offer an alternative mechanism that might have brought WD 1856 b close enough to generate a CE phase. Figure 2 shows one of the simulations in which Roche-lobe overflow and therefore CE evolution is triggered (black line). This simulation also illustrates that the assumption for initially circular planetary orbits in our reconstruction algorithm is reasonable as tidal forces circularize the orbit before dynamically unstable mass transfer leads to CE evolution.

5 EVAPORATION DURING AND AFTER THE COMMON ENVELOPE PHASE

While stellar companions clearly survive orbiting within a CE (as long as they do not merge with the core of the giant star), this is not necessarily true for planetary mass companions. In fact, Nelemans & Tauris (1998) considered evaporating or merging planetary mass companions as a possible explanation for observed single low-mass white dwarfs without a stellar companion. In order to evaluate whether the planet candidate around WD 1856 would have survived inside the envelope, we here follow their approach.

As the planet will move inside the envelope during CE evolution, it can be completely evaporated. Soker (1998) suggested that this occurs if the local sound speed ($c_s$) in the envelope reaches the escape velocity ($v_{esc}$) of the planet, i.e.

$$c_s^2 \approx v_{esc}^2 \iff \gamma \frac{k_BT}{\mu m_u} \approx \frac{2GM_p}{R_p}, \quad (2)$$

where $R_p$ and $M_p$ are the radius and the mass of the planet, and $T$ is the temperature of the envelope at the distance from the core ($r$). Using this criterion and assuming the same temperature structure of the envelope as Nelemans & Tauris (1998), i.e.

$$T \approx 1.78 \times 10^6 \times (r/R_\odot)^{-0.85} \text{K}, \quad (3)$$

we can estimate at which separation form the core (the future white dwarf) a planet with a given mass and radius would be fully evaporated inside the giant stars envelope. For the measured parameters of WD 1856 we find that for separations exceeding 0.71$R_\odot$ the planet...
For them mass loss rate in the energy limited regime of irradiated giant planets assumed to occur at a Jupiter-mass planet, the transition between both regimes is usually scales with the square root of the EUV irradiation in the latter. For first case mass loss is proportional to the EUV irradiation while it be in the energy limited or the recombination limited regime. In the current position, we use simple scaling laws for hydrodynamic escape. could have survived this phase of strong EUV evaporation at its current white dwarf (Schreiber et al. 2019). To estimate whether WD1856b could have survived this phase of strong EUV evaporation at its current position, we use simple scaling laws for hydrodynamic escape.

For large EUV fluxes, mass loss due to hydrodynamic escape can be in the energy limited or the recombination limited regime. In the first case mass loss is proportional to the EUV irradiation while it scales with the square root of the EUV irradiation in the latter. For a Jupiter-mass planet, the transition between both regimes is usually assumed to occur at 10 000 erg cm\(^{-2}\)s\(^{-1}\) (Murray-Clay et al. 2009). For the mass loss rate in the energy limited regime of irradiated giant planets we used (Murray-Clay et al. 2009):

\[
M = \frac{\epsilon F_{\text{EUV}} R_p^3}{G M_p K(\xi)}
\]  

where \(F_{\text{EUV}}\) is the incident EUV flux, and \(\epsilon\) the efficiency of using the incident energy, which we set to \(\epsilon = 0.3\) (Murray-Clay et al. 2009; Owen & Alvarez 2016). As WD1856b is quite close to the white dwarf, where the Roche-lobe \(R_{\L}\) and planet radius become somewhat comparable, mass loss is slightly enhanced. This is accounted for by the correction term \(K(\xi = R_{\L}/R_p)\) for which we used equation 17 from Erkaev et al. (2007). We calculated the EUV fluxes from the same model spectra used in Schreiber et al. (2019); Gänside et al. (2019) and used the above equations to estimate the mass loss rate. Figure 3 shows the resulting mass loss rate as a function of effective temperature (and cooling age). The total mass loss is clearly negligible and we therefore conclude that neither during nor after CE evolution the planet was significantly affected by evaporation.

**6 CONCLUDING DISCUSSION**

We have re-evaluated CE evolution as a possible mechanism to explain the existence of the gas giant planet candidate in a close 1.4 day orbit around the white dwarf WD 1856. Reconstructing the CE evolution we found that it offers a reasonable evolutionary scenario for this system. There exist plenty of mechanisms, including triple dynamics, that could have brought the planet to the location required to trigger CE evolution (separations of 1.69 – 2.35 au). The planet would also not have suffered important mass loss due to evaporation, neither during nor after CE evolution. Most importantly, we find that during CE evolution enough energy is available to unbind the envelope. If only 4 – 10 per cent of the available recombination energy contributed to expelling the envelope, the evolution of WD 1856 can be fully understood in the context of CE evolution, similar to the cases of the post CE binary stars IK Peg and KOI-3278 (Zorotovic et al. 2014).

Our results clearly show that if energy in addition to the orbital energy provided by the spiral-in of the planet contributed to expelling the envelope, CE evolution can explain the current configuration of WD 1856. In our simulations we assumed this additional energy to be recombination energy. However, in theoretical considerations of CE evolution the opinions on whether recombination energy can indeed significantly contribute to the envelope ejection process differ drastically. While Ivanova et al. (2015) and Webbink (2008) found that recombination energy can play an important role, others argue that most of the recombination energy is radiated away and that it therefore has a limited impact on the envelope ejection process (e.g. Sabach et al. 2017; Grichener et al. 2018; Soker et al. 2018). If recombination energy turns out to be indeed largely inefficient, other energy sources might have helped the planet to unbind the envelope of the giant. Examples for possible energy sources that have been discussed, but are usually considered les likely to provide important contributions, include accretion energy, nuclear energy, enthalpy (see Ivanova et al. 2013, for more details), or jets (Sabach et al. 2017). Potentially most interesting in the case of WD 1856, however, is the possibility that orbital energy of an additional giant planet played a role. This hypothetical additional planet could have initially been located somewhat closer to the star than WD 1856b and therefore did not survive the metamorphosis of the host star, but a fraction of its orbital energy could have helped WD 1856b in its effort to expel the giant envelope. Given that WD 1856 is not alone with its need for additional energy, and given the fact that several realistic mechanisms that might have provided this extra energy are in principal available, CE evolution clearly represents a reasonable scenario for the evolutionary history of WD 1856 and its close planetary companion.

Alternative scenarios that have been suggested for the formation of WD 1856 and its close planetary companion are planet-planet scattering (Vanderburg et al. 2020) and triple dynamics (‘O’Connor et al. 2020; Muño & Petrovich 2020). However, for all alternative scenarios to CE evolution, the likely membership of WD 1856 to the Galactic thin disc, limiting its age to \(\approx 10\) Gyr, poses a potential problem if the white dwarf mass is as small as measured by Vanderburg et al. (2020). This conclusion does not depend on the assumed metallicity of the white dwarf progenitor or the initial to final mass ratio. Table 2 lists the white dwarf progenitor masses for a sample of initial to final mass ratios and the corresponding main sequence lifetime derived using SSE, assuming a white dwarf mass of 0.52 M\(_{\odot}\). The time since the end of the main sequence until the progenitor becomes a white dwarf is around 1-1.7 Gyr, depending on the assumed metallicity. The cooling age, calculated from the Béard et al. (2020) cooling sequences, lies between 5.77 and 6.11 Gyr depending on the composition of the white dwarf atmosphere. Adding the post main sequence lifetime and the cooling age to the main sequence lifetimes listed in Table 2, we find that all of the listed initial to final mass
Table 2. Main-sequence mass and lifetime for a 0.52 M☉ white dwarf progenitor. The progenitor masses were derived using five different initial to final mass relations from the literature (first five rows) and the evolutionary code SSE (Hurley et al. 2000) with three different metallicities (last three rows). The main-sequence lifetimes were all derived using SSE, assuming solar metallicity for the first five rows.

| M⊥(M☉) | tms(Gyr) | IFMR reference |
|--------|----------|----------------|
| 1.54   | 6.45     | Weidemann (2000) |
| 1.403  | 3.35     | Williams et al. (2009) |
| 0.948  | 13.33    | Catalán et al. (2008) |
| 1.363  | 3.66     | Casewell et al. (2009) |
| 1.156  | 6.65     | Kalirai et al. (2008) |
| 0.885  | 14.51    | SSE (z = 0.01) |
| 1.020  | 10.20    | SSE (z = 0.02) |
| 1.170  | 6.83     | SSE (z = 0.03) |

ratios lead to total ages exceeding the age of the Galactic thin disc (10 Gyr), even assuming the shortest times derived for the post main sequence evolution and the white dwarf cooling. We therefore conclude that CE evolution is the most likely scenario for the history of WD 1856 if the white dwarf mass is ≈ 0.52 ± 0.05 M☉ as measured by Vanderburg et al. (2020). If the white dwarf mass is somewhat larger, i.e. ≈ 0.6 M☉, CE evolution remains one possibility together with alternative models such as close encounters with other planets in the system or Kozai-Lidov oscillations triggered by the distant companions.

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DATA AVAILABILITY

The data used in this article can be obtained upon request to Felipe Lagos (felipe.lagos@postgrado.uv.cl) and after agreeing to the terms of use.

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