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# A Red Giant Branch Common-envelope Evolution Scenario for the Exoplanet WD 1856 b

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## Abstract

We propose a common-envelope evolution scenario where a red giant branch (RGB) star engulfs a planet during its core helium flash to explain the puzzling system WD 1856+534, where a planet orbits a white dwarf (WD) of mass $M_{\rm WD} \simeq 0.52\,M_\odot$ with an orbital period of $P_{\rm orb} = 1.4$ days. At the heart of the scenario is the recently proposed assumption that the vigorous convection that core helium flash of RGB stars drive in the core excite waves that propagate and deposit their energy in the envelope. Using the BINARY-MESA stellar evolution code we show that this energy deposition substantially reduces the binding energy of the envelope and causes its expansion. We propose that in some cases RGB stars might engulf massive planets of $\gtrsim 0.01\ M_\odot$ during their core helium flash phase, and that the planet can unbind most of the mass of the bloated envelope. We show that there is a large range of initial orbital radii for which this scenario might take place under our assumptions. This scenario is relevant to other systems of close sub-stellar objects orbiting white dwarfs, like the brown dwarf–WD system ZTFJ003855.0+203025.5.

*Unified Astronomy Thesaurus concepts:* Star-planet interactions (2177); Exoplanet evolution (491); Red giant branch (1368)

## 1. Introduction

Vanderburg et al. (2020) reported the detection of a planet orbiting a white dwarf (WD; WD 1856+534; TIC 267574918) with a period of $P_{\rm orb} = 1.4$ days and an orbital separation of $a \simeq 0.02$ au (see also Alonso et al. 2021). They further argued that this relatively long orbital period of the planet candidate makes a common-envelope evolution (CEE) origin of the system less likely than a process where a third body scatters the planet to this orbit. They found the present mass of the WD to be $M_{\rm WD} = 0.518 \pm 0.055\,M_\odot$ and its cooling age as $5.85 \pm 0.5$ Gyr, implying that the progenitor mass should have been $\gtrsim 1.1\ M_\odot$. We will use for our study a stellar model with a zero age main sequence (ZAMS) mass of $M_{\rm ZAMS} = 1.6\,M_\odot$, but note that our scenario might work better for lower masses.

There were earlier claims for exoplanet candidates orbiting WDs (e.g., Gänsicke et al. 2019; Manser et al. 2019). One earlier claim for a planet candidate around an horizontal branch star by Setiawan et al. (2010) was refuted by Jones & Jenkins (2014). Setiawan et al. (2010) claimed for a planet with an orbital period of 16.2 days orbiting a metal-poor horizontal branch star (for other refuted claims for planets around horizontal branch stars see, e.g., Krzesinski et al. 2020). That refuted system had two extreme properties for a post-CEE surviving planet: a large semimajor axis of $\simeq 25 R_\odot$, and a large envelope mass of $\simeq 0.3\,M_\odot$. Bear et al. (2011) proposed a speculative scenario where a metal-poor red giant branch (RGB) star suffers a rapid expansion during its core helium flash and engulfs a planet (see criticism by Passy et al. 2012). The very extended RGB envelope has a low binding energy and the planet survives the CEE by ejecting the envelope (Section 2).

There are many studies of planets influencing RGB and asymptotic giant branch (AGB) stars (e.g., Nelemans & Tauris 1998; Soker 1998a; Siess & Livio 1999a; Nordhaus & Blackman 2006; Carlberg et al. 2009; Kunitomo et al. 2011; Mustill & Villaver 2012; Nordhaus & Spiegel 2013; Villaver et al. 2014; Aguilera-Gómez et al. 2016; Geier et al. 2016; Guo et al. 2016; Privitera et al. 2016; Rao et al. 2018; Schaffenroth et al. 2019; Jimenez et al. 2020; Kramer et al. 2020). It seems that when an RGB star engulfs a planet, there is a very low probability that the planet will survive the CEE because it cannot release enough orbital energy to unbind the envelope before it suffers destruction near the RGB core. Extra energy deposition to the envelope just before the CEE lowers the envelope binding energy, and might allow a massive planet of mass $M_{\rm p} \gtrsim {\rm few} \times M_{\rm J}$ to survive the CEE, where $M_{\rm J}$ is Jupiter mass.

In a new study, Bear et al. (2021) propose that waves that the vigorous convection during the core helium flash excite might cause the envelope of RGB stars to substantially expand within a few years. Here we use this expansion to propose (Section 2) and examine (Section 3) a CEE scenario for the formation of the planet–WD system WD 1856+534. There are other scenarios for the formation of the system WD 1856+534. One group of studies examine the formation of this system by the scattering-in of the planet to an orbit around the WD after the formation of the WD, either planet–planet scattering in a multiple-planets system (Maldonado et al. 2021), or scattering-in by a secondary star (or a tertiary star) in the system, i.e., the Lidov–Kozai effect (e.g., Muñoz & Petrovich 2020; Stephan et al. 2020; Vanderburg et al. 2020; O'Connor et al. 2021).

The other group of studies attribute the system WD 1856+534 to a CEE. Lagos et al. (2021) present the motivation to consider a CEE, and propose that the CEE takes place on the AGB. For their scenario to work they need an extra energy source (in addition to the orbital energy of the planet) to remove the entire envelope. We, instead, consider the CEE to take place on the RGB. They also show that the planet survives the post-CEE against evaporation. We build on these parts of their study. Chamandy et al. (2021) attribute the extra energy source to another planet in the system that entered the RGB or AGB envelope at an earlier phase, and deposited a large fraction of the envelope binding energy. Such a process influences the evolution of the planet that orbits further out and might help it to survive (e.g., Bear et al. 2011; Lagos et al. 2021).

## 2. The Basic Scenario and Assumptions

The unique ingredient of the scenario that we deal with here for an RGB star to engulf an exoplanet(s) during its core helium flash is that, during the core helium flash on the termination of the RGB phase, the vigorous helium burning in the core leads to the deposition of energy in the envelope. This energy causes the envelope expansion.

Bear et al. (2011) considered the energy source to be the ignition of hydrogen at the base of the hydrogen-rich envelope in metal-poor stars. They based their speculative scenario on the results of Mocák et al. (2010), who calculated hydrogen ignition by the core helium flash, a process that releases $\approx 1 \times 10^{48}$ erg of nuclear energy during the first year. Bear et al. (2011) manually added an energy of $E_{\rm in} = 8.5 \times 10^{46}$ erg just above the hydrogen-burning shell in a time period of 7 yr at an average power of $L_{\rm in} = 10^5\,L_\odot$ and found the star to expand by a factor of about 4. We cannot apply this scenario to stars with solar metallicity or higher.

We apply the scenario that Bear et al. (2021) propose where waves that the vigorous convection during the core helium flash excite propagate to the envelope and deposit their energy there. Bear et al. (2021) base their scenario on the results of Quataert & Shiode (2012) and Shiode & Quataert (2014), who studied the propagation from the core to the envelope of waves that the vigorous core convection in pre-supernova massive stars excite. The waves deposit their energy in the envelope, causing it to expand (e.g., Mcley & Soker 2014; Fuller 2017).

For their model of $M_{\rm ZAMS} = 1.6\,M_\odot$ that we use here, Bear et al. (2021) apply a formula from Lecoanet & Quataert (2013) and find the total energy that the waves might deposit to the envelope to be $E_{\rm wave,0} = 2.1 \times 10^{47}\ {\rm erg} = 1.7 \times 10^6\,L_\odot$ yr. They took a conservative approach and deposited less than this energy to the envelope at a constant luminosity $L_{\rm W} = \beta E_{\rm wave,0}/\Delta t_{\rm dep} = 4.3 \times 10^5 \beta L_\odot$ during a time period of $\Delta t_{\rm dep} = 4$ yr and with $\beta \ll 1$. Because of the uncertainty in the location in the envelope where the waves deposit their energy, they examined three prescriptions. They deposited the wave energy to the envelope outer $\xi M_{\rm env}$ mass, with $\xi = 80\%$, $\xi = 50\%$, or $\xi = 20\%$, and with a constant power per unit mass. The core and envelope mass when we deposit the wave energy are $M_{\rm core,b} = 0.45\,M_\odot$ and $M_{\rm env,b} = 1.01\,M_\odot$, respectively (the subscript "b" stands for "just before energy deposition"). In Figure 1 we present the response of the envelope radius to wave-energy deposition for four values of wave power as Bear et al. (2021) present it.

Based on this rapid expansion of the RGB star we propose the following scenario for the formation of the planet−WD system WD 1856+534. The rapid expansion during the core helium flash brought the RGB to engulf one or more of its exoplanets. The planet spirals-in in a time period of several years alongside the contraction of the RGB star. According to Vanderburg et al. (2020) the WD mass is $M_{\rm WD} = 0.518 \pm 0.055\,M_\odot$ and the orbital separation is about $a = 4\,R_\odot$. For a stellar remnant mass of 0.52 $M_\odot$ and an orbital separation of $a = 4R_\odot$ the planet of mass $M_{\rm p}$ releases an orbital energy of

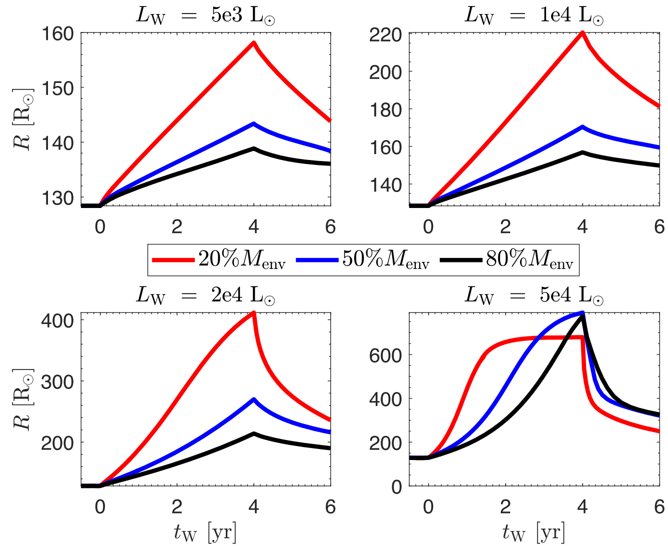

**Figure 1.** Radius as function of time as a result of wave-energy deposition into the RGB envelope of a stellar model with initial mass of $M_{\rm ZAMS} = 1.6\,M_\odot$. Each panel shows the results for one value of the waves power $L_{\rm W}$ as indicated, and for three cases according to the outer envelope mass into which the waves deposit their energy. In all cases, the energy deposition time period lasts for 4 years. We set $t_{\rm W} = 0$ at the beginning of energy deposition (from Bear et al. 2021).

$$E_{\rm orb} = 2.5 \times 10^{45} \left( \frac{M_{\rm p}}{0.01\,M_\odot} \right) {\rm erg}. \tag{1}$$

In our simulations (Section 3.2) we use a planet of mass $M_{\rm p} = 0.01\,M_\odot = 10.5 M_{\rm J}$.

The binding energy of the RGB envelope residing above mass coordinate $m = 0.52\,M_\odot$ without wave-energy deposition is $E_{\rm env,bind,b}(0.52) = 1.2 \times 10^{46}$ erg. We simulate the evolution of planets with two cases of wave-energy deposition $(L_{\rm W}, \xi) = (2 \times 10^4\,L_\odot, 20\%)$ and $(L_{\rm W}, \xi) = (5 \times 10^4\,L_\odot, 80\%)$. The binding energy of the envelope that resides above mass coordinate $m = 0.52\,M_\odot$ at the end of wave-energy deposition in the first case is $E_{\rm env,bind,20}(0.52) = 6.4 \times 10^{45}$ erg. The ratio $E_{\rm orb}/E_{\rm env,bind,20}(0.52) \simeq 0.4$ implies that the spiraling-in planet can unbind a large fraction of the envelope.

In the second case, the energy of that envelope mass becomes positive, i.e., a negative binding energy of $E_{\rm env,bind,80}(0.52) = -6.2 \times 10^{45}$ erg. The envelope does not unbind itself despite its positive energy because the envelope ejection time, which is about the dynamical time of the extended envelope $\simeq 2$ yr, is longer than the time that the envelope radiates this extra energy out, $\approx |E_{\rm env,bind,80}(0.52)|/L_{\xi=80} \simeq 1$ yr, where $L_{\xi=80} \simeq 5 \times 10^4\,L_\odot$ is the maximum luminosity that the star reaches at $t_{\rm W} = 4$ yr (Bear et al. 2021). Nonetheless, we expect a highly enhanced mass loss during this phase, something that MESA does not include. The highly enhanced mass loss rate takes place after the planet already approaches the envelope because of tidal forces and spins the envelope up (before it even enters the envelope and after it enters the envelope). Because the planet is already falling toward the envelope and tidal forces are already large, the extra mass loss is not sufficient to prevent engulfment.

There are other planet-induced effects that can enhance the mass loss rate. Excitation of p-waves by the planet (e.g., Soker 1993) and the spinning-up of the envelope (e.g., Soker 1998b; Nordhaus & Blackman 2006) can facilitate formation of dust that more efficiently couples the stellar radiation to wind, and by that enhances the mass loss rate (e.g., Soker 1998b; Glanz & Perets 2018; Iaconi et al. 2019). We suggest that, due to the rapid expansion during the core helium flash, the planet manages to eject the envelope and survive.

We attribute the same scenario for the formation of the system ZTFJ003855.0+203025.5 of a brown dwarf of mass $\simeq 0.059\,M_\odot$ orbiting a WD of mass $\simeq 0.5\,M_\odot$ with a semimajor axis of $2.0\,R_\odot$ as van Roestel et al. (2021) reported recently.

## 3. Planet Engulfment during the Core Helium Flash

### 3.1. Numerical Setting

We use MESA-BINARY version 10398 (Paxton et al. 2011, 2013, 2015, 2018, 2019). We divide our numerical simulations to two numerical phases; in all numerical phases in our binary inlist we follow the example of MESA-BINARY *star plus point mass*. We set tidal for the binary system (*do tidal sync* = *.true.*).

In numerical phase A we follow the evolution of a $M_{\rm ZAMS} = 1.6\,M_\odot$ star using the example of 1*M pre ms to wd*, orbited by a planet of mass $M_{\rm p} = 0.01\,M_\odot$. We treat the planet as a point mass. For each case of an initial orbital radius $a_0$ we find the time when the radius is maximal (this is consistent with the He flash) and we stop this numerical phase at 4 yr before the maximal radius is achieved. In numerical phase B that lasts from $t_{\rm W} = 0$ to $t_{\rm W} = 4$ yr, we manually insert energy (the wave energy) in the src folder in the run-star-extra.f in the subroutine: subroutine energy-routine file, when we set the pointer of *other energy* to true. As in Bear et al. (2021) we insert energy at a constant power $L_{\rm W}$ into the outer $\xi M_{\rm env}$ zone of the envelope. We analyze the influence of energy deposition on the radius of the star and on the orbital separation (radius).

### 3.2. Orbital Evolution

In all simulations we take a planet of mass $M_{\rm p} = 0.01\,M_\odot = 10.5 M_{\rm J}$ and circular orbits. For each of the two wave-energy deposition cases we search for the range of initial orbital radii (semimajor axes) $a_{0,\rm min} \lesssim a_{0,\rm in} \lesssim a_{0,\rm max}$, for which the RGB star engulfs the planet during its rapid expansion following the core helium flash (but not before that). We first determine that for the planet to survive to the core helium flash its initial orbital radius should be $a_0 > a_{0,\rm min} \simeq 440\,R_\odot$. In Figure 2 we present the evolution on this boundary of engulfment without wave-energy deposition, i.e., we present two cases with close initial orbital radii to each other: in one case the RGB star engulfs the planet, and in the other case (that has a few percent larger initial radius) the planet avoids engulfment.

For the cases of $(L_{\rm W},\ \xi) = (2\times10^4\,L_\odot,\ 20\%)$ and $(L_{\rm W},\ \xi) = (5\times10^4\,L_\odot,\ 80\%)$ we find the initial orbital radii for which the RGB star engulfs our planet during its core helium flash (the four years during which we deposit the wave energy) to be

$$\begin{aligned} &435\ R_\odot \lesssim a_{0,\rm in,20} \lesssim 540\ R_\odot \quad \text{and} \\ &435\ R_\odot \lesssim a_{0,\rm in,80} \lesssim 1160\ R_\odot, \end{aligned} \tag{2}$$

respectively. The uncertainties in the values of the above boundaries that we find with MESA are $\simeq\pm2\%$ (not including uncertainties in some chosen parameters that we use in MESA). In Figure 3 we present the evolution of the RGB radii and orbital separations during the period of the wave-energy deposition for an initial orbital separation very close to the upper limit for planet engulfment.

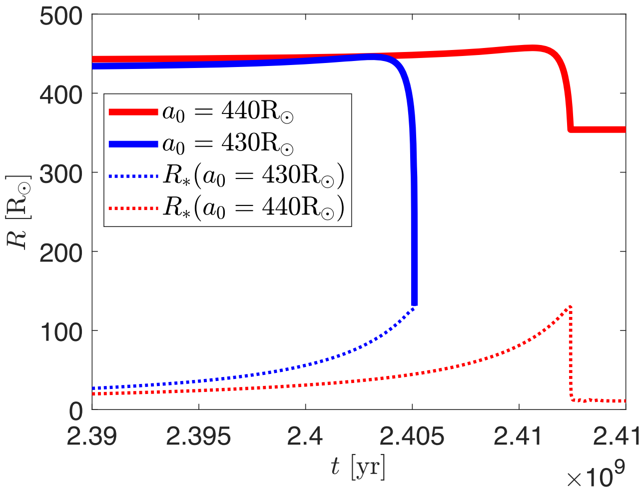

**Figure 2.** RGB radius (dotted line) and the orbital radius of the $M_{\rm p} = 0.01\,M_\odot$ planet (thick solid line) as function of time at the end of the RGB evolution without wave-energy deposition. The blue lines represent the case of an initial orbital radius (at ZAMS of the star) of $a_0 = 430\,R_\odot$ for which the RGB star engulfs the planet, and the red lines represent the case of an initial orbital radius of $a_0 = 440\,R_\odot$ for which the RGB star does not engulf the planet.

The main conclusions from our simulations that aim at explaining the planet–WD system WD 1856+534 are that, under our assumptions, (i) the orbital energy that the planet releases is a significant fraction of the envelope binding energy after wave-energy deposition, and (ii) there is a large range of initial planetary orbits for which the RGB engulfs the planet during the core helium flash.

## 4. Summary

We propose a scenario to explain the puzzling system WD 1856+534 where a planet orbits a WD of mass $M_{\rm WD} \simeq 0.52\,M_\odot$ with an orbital period of $P_{\rm orb} = 1.4$ days (Vanderburg et al. 2020). We chose the parameters of our numerical simulations, $M_{\rm ZAMS} = 1.6\,M_\odot$ and $M_{\rm p} = 0.01\,M_\odot$, to comply with this system. We note though that the planet might be somewhat more massive (but still be a planet) and that the initial stellar mass can be as low as $M_{\rm ZAMS,min} = 1.1\,M_\odot$ (Vanderburg et al. 2020), both of which make our scenario more likely even.

We base our study on the yet to be tested assumption of Bear et al. (2021) that the vigorous core convection during the core helium flash of RGB stars excite waves that propagate to the envelope and deposit their energy in the envelope, causing its expansion (Figure 1) and substantially reducing its binding energy. It is sufficient that the energy that the waves carry during their few years activity is only $\simeq$5%–10% of the possible wave energy that Bear et al. (2021) estimate from studies of massive stars (Lecoanet & Quataert 2013).

Our calculations under the above assumption that convection-induced waves cause RGB envelope expansion show that (i) an $M_{\rm p} \gtrsim 0.01\,M_\odot$ planet that spirals-in inside the bloated RGB envelope can release sufficient orbital energy to unbind a significant fraction of the loosely bound envelope, and (ii) there

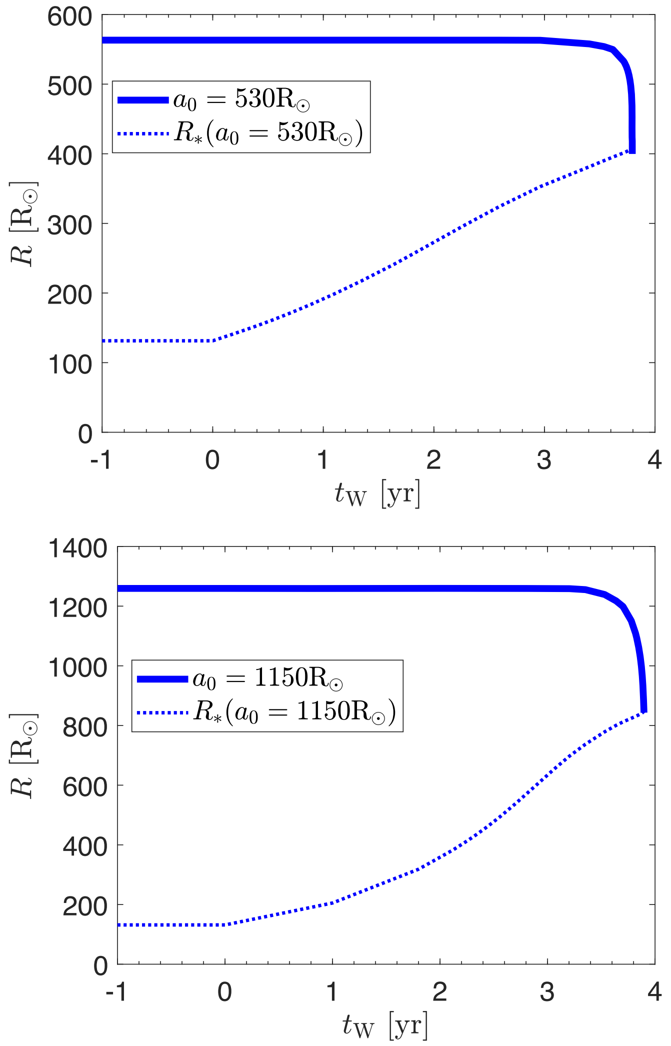

**Figure 3.** RGB radius (dotted line) and the orbital radius of the $M_p = 0.01\ M_\odot$ planet (thick solid line) as function of time around the time of wave-energy deposition to the envelope, $2.41 \times 10^9$ yr. Both cases are for initial planetary orbits $a_0$ close to the upper boundary of planet engulfment. Because of mass loss the orbital radius increases by the time we deposit the wave energy. We start energy deposition at $t_W = 0$. Top panel: the case of $(L_W, \xi) = (2 \times 10^4\ L_\odot$, 20%), i.e., wave power of $L_W = 2 \times 10^4\ L_\odot$ and energy deposition into the outer $\xi = 20\%$ mass of the envelope. Bottom panel: The case of $(L_W, \xi) = (5 \times 10^4\ L_\odot$, 80%).

is a large range of initial planetary orbits for which the RGB engulfs the planet during the core helium flash (Equation (2)).

As we mentioned in Section 1 some earlier studies noticed that an inner planet that enters the RGB (or AGB) envelope before the planet that eventually survives might remove envelope mass and allow the surviving planet to eject most of the envelope and survive. The presence of an inner planet or more can also increase the allowed parameter space for our proposed scenario.

We consider our proposed core helium flash wave-energy scenario to be a promising explanation to the planet–WD system WD 1856+534 and similar systems of sub-stellar objects closely orbiting WDs, e.g., the brown dwarf–WD system ZTFJ003855.0+203025.5 that van Roestel et al. (2021) recently analyzed.

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## Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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## References

Aguilera-Gómez, C., Chanamé, J., Pinsonneault, M. H., & Carlberg, J. K. 2016, ApJL, 833, L24
Alonso, R., Rodríguez-Gil, P., Izquierdo, P., et al. 2021, A&A, 649, A131
Bear, E., Merlov, A., Arad, Y., & Soker, N. 2021, arXiv:2106.00582
Bear, E., Soker, N., & Harpaz, A. 2011, ApJL, 733, L44
Carlberg, J. K., Majewski, S. R., & Arras, P. 2009, ApJ, 700, 832
Chamandy, L., Blackman, E. G., Nordhaus, J., & Wilson, E. 2021, MNRAS, 502, L110
Fuller, J. 2017, MNRAS, 470, 1642
Gänsicke, B. T., Schreiber, M. R., Toloza, O., et al. 2019, Natur, 576, 61
Geier, S., Kupfer, T., Schaffenroth, V., & Heber, U. 2016, in IAU Symp. 317, The General Assembly of Galaxy Halos: Structure, Origin and Evolution, ed. A. Bragaglia et al. (Cambridge: Cambridge Univ. Press), 302
Glanz, H., & Perets, H. B. 2018, MNRAS, 478, L12
Guo, J., Lin, L., Bai, C., & Liu, J. 2016, Ap&SS, 361, 122
Iaconi, R., Maeda, K., De Marco, O., Nozawa, T., & Reichardt, T. 2019, MNRAS, 489, 3334
Jimenez, R., Gråe JØrgensen, U., & Verde, L. 2020, JCAP, 10, 027
Jones, M. I., & Jenkins, J. S. 2014, A&A, 562, A129
Kramer, M., Schneider, F. R. N., Ohlmann, S. T., et al. 2020, A&A, 642, A97
Krzesinski, J., Blokesz, A., Siwak, M., et al. 2020, A&A, 642, A105
Kunitomo, M., Ikoma, M., Sato, B., Katsuta, Y., & Ida, S. 2011, ApJ, 737, 66
Lagos, F., Schreiber, M. R., Zorotovic, M., Gänsicke, B. T., Ronco, M. P., & Hamers, A. S. 2021, MNRAS, 501, 676
Lecoanet, D., & Quataert, E. 2013, MNRAS, 430, 2363
Maldonado, R. F., Villaver, E., Mustill, A. J., Chávez, M., & Bertone, E. 2021, MNRAS, 501, L43
Manser, C. J., Gänsicke, B. T., Eggl, S., et al. 2019, Sci, 364, 66
Mcley, L., & Soker, N. 2014, MNRAS, 445, 2492
Mocák, M., Campbell, S. W., Müller, E., & Kifonidis, K. 2010, A&A, 520, A114
Muñoz, D. J., & Petrovich, C. 2020, ApJL, 904, L3
Mustill, A. J., & Villaver, E. 2012, ApJ, 761, 121
Nelemans, G., & Tauris, T. M. 1998, A&A, 335, L85
Nordhaus, J., & Blackman, E. G. 2006, MNRAS, 370, 2004
Nordhaus, J., & Spiegel, D. S. 2013, MNRAS, 432, 500
O'Connor, C. E., Liu, B., & Lai, D. 2021, MNRAS, 501, 507
Passy, J.-C., Mac Low, M.-M., & De Marco, O. 2012, ApJL, 759, L30
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3
Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4
Paxton, B., Marchant, P., Schwab, J., et al. 2015, ApJS, 220, 15
Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, ApJS, 234, 34
Paxton, B., Smolec, R., Schwab, J., et al. 2019, ApJS, 243, 10
Privitera, G., Meynet, G., Eggenberger, P., et al. 2016, A&A, 591, A45
Quataert, E., & Shiode, J. 2012, MNRAS, 423, L92
Rao, S., Meynet, G., Eggenberger, P., et al. 2018, A&A, 618, A18
Schaffenroth, V., Barlow, B. N., Geier, S., et al. 2019, A&A, 630, A80
Setiawan, J., Klement, R. J., Henning, T., et al. 2010, Sci, 330, 1642
Shiode, J. H., & Quataert, E. 2014, ApJ, 780, 96
Siess, L., & Livio, M. 1999a, MNRAS, 304, 925
Soker, N. 1993, ApJ, 417, 347
Soker, N. 1998a, AJ, 116, 1308
Soker, N. 1998b, MNRAS, 299, 1242
Stephan, A. P., Naoz, S., & Gaudi, B. S. 2020, arXiv:2010.10534
van Roestel, J., Kupfer, T., Bell, K. J., et al. 2021, arXiv:2105.08687
Vanderburg, A., Rappaport, S. A., Xu, S., et al. 2020, Natur, 585, 363
Villaver, E., Livio, M., Mustill, A. J., & Siess, L. 2014, ApJ, 794, 3