Evolving R Coronae Borealis Stars with \textit{MESA}

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ABSTRACT

The R Coronae Borealis (RCB) stars are rare hydrogen-deficient, carbon-rich supergiants. They undergo extreme, irregular declines in brightness of many magnitudes due to the formation of thick clouds of carbon dust. Two scenarios have been proposed for the origin of an RCB star: the merger of a CO/He white dwarf (WD) binary and a final helium-shell flash. We used the results of WD mergers in 3D hydrodynamics codes to provide the initial conditions for the 1D \textit{MESA} (Modules for Experiments in Stellar Astrophysics) stellar evolution code including nucleosynthesis. We constructed post-merger spherical models based on realistic merger progenitors and on inputs from our hydrodynamical simulations, and then followed the evolution into the region of the HR diagram where the RCB stars are located. We also investigated nucleosynthesis in the dynamically accreting material of CO/He WD mergers which may provide a suitable environment for significant production of \(^{18}\text{O}\) and the very low \(^{16}\text{O}/^{18}\text{O}\) values observed.

Our \textit{MESA} modeling consists of engineering the star by adding He-WD material to an initial CO-WD model, and then following the post-merger evolution using a nuclear-reaction network to match the observed RCB abundances as it expands and cools to become an RCB star. We follow the later evolution beyond the RCB phase to determine the stars’ likely lifetimes. The relative numbers of known RCB and Extreme Helium stars correspond well to the lifetimes predicted from the \textit{MESA} models.

Key words: stars: evolution – white dwarfs – binaries: close – stars: abundances

1 INTRODUCTION

The R Coronae Borealis (RCB) stars make up a class of rare hydrogen-deficient supergiants that may be the result of a white-dwarf (WD) merger event (Clayton 2012). The RCB stars are best known for sudden declines in brightness of 8 magnitudes or more at irregular intervals caused by clouds of carbon dust forming near the atmospheres of the stars, which are later dissipated by radiation pressure. Only about 150 RCB stars are known in the Galaxy (Clayton 2012; Tisserand et al. 2013). There are also five hydrogen-deficient carbon (HdC) stars that mimic RCB stars spectroscopically, but do not show declines in brightness or IR excesses (Warner 1967). The RCB stars may be the result of a rare form of stellar evolution or are in an evolutionary phase that lasts only a short time. In addition to their extreme hydrogen deficiency, RCB stars show uniquely low \(^{16}\text{O}/^{18}\text{O}\), large \(^{12}\text{C}/^{13}\text{C}\), and enhanced s-process elements which are all consistent with partial He-burning (Clayton et al. 2007).

Two scenarios have been suggested for producing an RCB star: the double degenerate (DD) and the final helium-shell flash (FF) models (Iben et al. 1996; Saio & Jeffery 2002). In the DD model, an RCB star is the result of a merger between a CO- and a He-white dwarf (WD) (Webbink 1984). In the FF model, a star evolving into a WD undergoes a final helium-shell flash and expands to supergiant size (Fujimoto 1977). The preponderance of the evidence seems to support the WD-merger scenario (Clayton et al. 2007, 2011; Clayton 2012).

We have been using the 1D \textit{MESA} (Modules for Experiments in Stellar Astrophysics) stellar evolution code including nucleosynthesis to construct post-merger spherical models based on realistic merger progenitors and on 3D hydrodynamical simulations of the merger (Staff et al. 2012, 2018). We followed the evolution into the region of the HR diagram where RCB stars are located (Staff et al. 2012; Menon et al. 2013; Staff et al. 2018). Previous studies using grid and SPH hydrodynamics codes as well as \textit{MESA}, have had difficulty
reproducing all of the abundances seen in the RCB stars including the $^{16}$O/$^{18}$O ratio (Longland et al. 2011; Staff et al. 2012; Menon et al. 2013; Zhang et al. 2014; Staff et al. 2018).

In this paper, we use MESA to study the evolution of 0.8–1.05 $M_\odot$ post-merger objects with the aim of reproducing the observed nucleosynthetic signatures of RCB Stars. Our MESA modeling consists of two steps. First, we mimic the WD merger event by applying “stellar engineering” to an initial CO-WD model by adding He-WD material to account for the newly merged material and then by applying an entropy adjusting procedure (Shen et al. 2012; Schwab et al. 2016b). Second, we follow the post-merger evolution using a nuclear-reaction network including the effects of convective and rotational instabilities to the mixing of material in order to match the observed RCB abundances. MESA follows the evolution of the merger product as it expands and cools to become an RCB star. We then examine the surface abundances and compare them to the observed RCB abundances (Asplund et al. 2000; Clayton et al. 2007; Hema et al. 2017). We also investigate how long fusion continues in the He shell near the core and how this processed material is mixed up to the surface of the star. We then model the later evolution of RCB stars to determine their likely lifetimes and endpoints when they have returned to being WDs.

2 CREATING CO/HE WHITE DWARF POST–MERGER OBJECTS WITH MESA

To simulate the evolution of RCB stars, we use the MESA 1D spherically-symmetric, stellar-evolution code (Paxton et al. 2010, 2013, 2015). Therefore, there are some concessions in terms of reproducing a realistic structure of a CO/He-WD post–merger object. In particular, the structure of such an object right after merger as shown by 3D hydrodynamical simulations is composed of three components: a cold core (the accreting CO-WD), a hot, puffy corona and a disk (composed of the disrupted He-WD material) (Staff et al. 2012, 2018). The photosphere will not have a spherical but rather an elongated shape, as shown in multiple hydrodynamical simulations (Saio & Jeffery 2002; Motl et al. 2007; Yoon et al. 2007; Longland et al. 2011; Staff et al. 2012; Zhu et al. 2013; Zhang et al. 2014). However, as described below in Section 4, the merger object becomes spherical in only a few years.

To create an approximate CO/He-WD post-merger evolution and set the initial conditions for the MESA evolution calculation, we follow a multi–step process similar to that used by Shen et al. (2012) and Schwab et al. (2016a). To produce the initial He and CO WD models, we used the MESA test-suite cases, make_he_wd and make_co_wd, coupled with our choice of two nuclear reaction networks (mesa_75.net and Sagb_HeNa_MgAl.net). The final He- and CO-WD structures are computed by simulating the entire stellar evolution of 1.5 $M_\odot$ and 6 $M_\odot$ stars, respectively, from the ZAMS to the WD stage when the luminosity drops to $L = 10^{-2} L_\odot$.

Then, we computed the CO- and He-WD compositional structures independently in MESA for two nuclear-reaction network choices: the “large” (mesa_75.net) network with 75 species ranging from neutrons to $^{27}$Al (Table 2) and the “reduced” (sagb_HeNa_MgAl.net) network with species ranging from neutrons to $^{27}$Al (Table 2). The “reduced” network is chosen because it is a subset of the “large” network and allows for faster computing times. For the He-WD, we compute an average including the entire mass of the model star assuming that the disrupted He-WD material will be heavily mixed in the process of becoming the corona of the post–merger object. The final CO-WD is computed using a radial mass fraction profile.

We evolve a solar metallicity star with mass equal to the desired mass of the post–merger object and with nuclear burning turned off to a stage when the core becomes degenerate. We designate that phase to be when $\eta_c = 0.5$, where $\eta_c \sim \mu/k_BT$ and $\eta_c$ is the degeneracy parameter in the central zone, $\mu$ the electron chemical potential and $T$ the temperature. Subsequently, we restart the calculation in order to adjust the composition of the entire star to one corresponding to the CO-WD calculated independently in MESA during the first step described earlier. Then, we allow the degenerate star to cool down to a core temperature of $\sim 1.6 \times 10^7$ K. In the next step, we select the mass coordinate that sets the desired boundary between the CO- and the He-WD portions of the post–merger object and adjust the composition from that point to the surface using the pre-computed profile for the He-WD. At this stage, we have a composite fully degenerate CO/He object. Thus, the final step is to adjust the envelope structure to mimic the size and characteristics of the cold CO core and puffy He corona that make up the post–merger object following the fast and slow accretion phase seen in hydrodynamic simulations of CO/He-WD mergers (Staff et al. 2012; Zhang et al. 2014). To do so, we use an entropy adjusting procedure as detailed in Shen et al. (2012). Entropy is added to the envelope until it expands to a desired radius while nuclear burning, neutrino cooling, and chemical mixing are kept turned off.

Figure 1 shows the engineered $T$–$p$ structure of the 0.8 $M_\odot$ He/CO-WD post–merger object before and after the envelope entropy injection phase. Figure 2 shows the temperature ($T$) profile of the final post–merger object for two cases (low and high entropy injection). This Figure can be compared to Figure 4 of Zhang et al. (2014). The amount of entropy injected in the envelope sets the initial radius as well as peak temperature in the hot shell of the post–merger object. Following the entropy adjustment process and depending on how much entropy is injected in the envelope of the post-merger object, the radius of the He-WD corona will increase accordingly. In Figures 1 and 2, two examples are shown, the “R2” case resulting from 10% more entropy injected than in the “R1” case. Higher entropy and a more extended envelope results in a somewhat lower peak temperature (Figure 2) and less C-burning (Figure 1) in the hot, He-burning shell. Note how the tip of the density-temperature profile barely edges into the C-burning region for the “R2” case.

3 THE NUCLEAR NETWORK

Previous MESA models of RCB stars, and indeed other stellar models, have been forced to rely on post-processing (e.g., Menon et al. 2013). MESA produced a time-evolved thermodynamical profile of temperature and density and then this profile was used as the input for a separate, dedicated large
nuclear network. This method suffers from several disadvantages, the primary one being that the feedback between nucleosynthesis and the rest of the stellar evolution is missing. Since nuclear cross sections are a function of temperature, and this is the primary thermodynamic variable from stellar evolution, we expect the interplay between the two to be a vital part of the model. This is further complicated by the fact that the physics and the nuclear network are usually not fully coupled. However, dedicated nuclear network codes such as NuGrid have the advantage of being easily scalable to very large networks with relatively little computational cost. Our previous work with MESA used post-processing methods, and performed the nucleosynthesis separately using NuGrid (Menon et al. 2013).

MESA recently significantly upgraded its capabilities in this area (Paxton et al. 2015). The nuclear network is now fully coupled to the stellar evolution. Additionally, a Heger-style (Rauscher et al. 2002) adaptive network option has been added. In the case of an adaptive nuclear network, the stellar composition is examined in each time step. The mass fraction of each species is tested to be above a user-defined threshold in any cell in the model in order to be included in the next time step. An additional user-defined threshold determines whether those nuclei which can be reached by common proton, neutron, or alpha reactions are added to the network, up to some maximum Z, N, and A values, which are also user defined. Then, every reaction that connects the species within the new network is added, with the reaction rate derived from REACLIB or other database. Small, fixed networks, often used in stellar evolution, are limited in their capability to inform nuclear physics as they often ignore species with low mass fractions and reactions with low cross sections. As standard stellar environments are increasingly explored, exotic scenarios will become the focus more and more. Thus, this new MESA capability is a welcome development.

As such it is important to choose the correct network within MESA. The primary goals of this study are to match the RCB observations (Asplund et al. 2000; Jeffery et al. 2011), and also to compare our new results with previous MESA models (Longland et al. 2011; Menon et al. 2013; Zhang et al. 2014). However, MESA has increased capabilities, in addition to the new nuclear network features, so a strict comparison is not possible. Of special interest are $^{12}\text{C}/^{13}\text{C}$, $^{16}\text{O}/^{18}\text{O}$, F, Li, and various s-process elements.

The optimal network must include all of these species as well as the intermediate nuclei. It is possible to define a custom network, as MESA will accept any list of species and
Figure 2. Temperature profiles for the final, entropy–adjusted post–merger objects illustrating the hot shell defining the interface between the CO and the He-WD material. Two cases are shown, one for a compact (radius $R_1$; solid curve) and one for a more extended (radius $R_2$; dashed curve) post–merger envelope with a cooler hot–shell.

4 POST–MERGER EVOLUTION

We compute the evolution of a suite of CO/He post–merger objects spanning the relevant parameter space in order to investigate the sensitivity of RCB properties to initial conditions and physical mechanisms. In particular, we compute the evolution of post–merger objects with masses 0.80, 0.85, 0.90, 0.95, 1.00 and 1.05 $M_\odot$. For the 0.80 $M_\odot$ model, we compute cases varying the initial radius, rotation rate, H abundance in the He-WD, choice of nuclear reaction network, and CO- to He-WD mass ratio. The results are compared to the observed characteristics of the RCB stars.

The standard initial conditions that we adopted for all of our post–merger models are:
- Radii = $-1.12 < \log(R/R_\odot) < -0.74$
5 RESULTS

5.1 Comparison with Previous Work

In the previous MESA modeling by Menon et al. (2013), the abundance profile was somewhat contrived. The four-zone model consisted of a core based on the pre-merger CO-WD, a shell of mixed He-WD material, and two additional zones added to the model, a non-physical “buffer” zone, as well as the so-called shell-of-fire where temperatures are high enough for He-burning (Staff et al. 2012). The latter is thought to be a real feature, however, in an ideal scenario it would arise naturally from the physics of the evolving star. Menon et al. manufactured this behavior using an additional mixing routine added to the built in MESA routines. The buffer zone is 97% He with trace amounts of H and N, while the shell-of-fire consists of a mixture of material from the He- and CO-WDs. The abundance results were calculated using post-processing in NuGrid. The post-merger abundance profile used in this work was derived by following the evolution of the progenitors (using methods described above). Also, no artificial mixing routines were included after the merger, and the nucleosynthesis was calculated along with the stellar evolution.

Longland et al. (2011) report 3D SPH simulations of 0.8+0.4 \( M_\odot \) CO/He-WD mergers leading to RCB stars. These resulted from fast and slow accretion phases producing a core (CO-WD) surrounded by a He corona and an ongoing accretion disk. Only a little mass is lost in the merger process and a hot He-layer forms in the transition region from the CO- to the He-WD. Over the course of the 3D SPH merger simulations, density/temperature radial averages are calculated and the composition profile is a five zone model; three zones in the CO-WD (CO-, He- and H-rich) and two zones (H- and He-rich) in the He-WD. Though this was a 3D simulation of the dynamical merger, it was reduced to 1D radial averages to do the nuclear burning using this 5 zone compositional profile, with post-processing nucleosynthesis.

The nuclear network contained 327 isotopes from H to Gallium in their (very under-resolved) five zone model. The models presented in our study have better resolution (~1000s of zones, and burning is computed in all zones where permitted by local conditions) but fewer isotopes (75). Our models also use the latest data to predict energy release rates from nuclear reactions built into MESA using the REACLIB and WEAKLIB (standard) rate libraries. Longland et al. (2011) only calculate energy release rates for 14 \( \alpha \)-capture (He-burning) nuclei, which dominate the energy generation and suggest this is only 1% different from including whole network to Ga. This is one of the assumptions in the post-processing, which does not account for the extreme conditions and intense interplay between \( T \) and reaction rate in exotic or explosive environments. The Longland et al. (2011) models don’t include stellar evolution of the post-merger star which our models do, as well as including rotation and mass-loss. Their models simply post-process the density/temperature profiles and then turn on He-burning for the five zones if conditions are right. The new models presented here have self-consistent evolution with better resolution of the post-merger object and nucleosynthesis with energy generation for 75 isotopes and all other (mixing, mass-loss) properties. We also predict time-scales and stellar evolution tracks.

Zhang et al. (2014) created a custom isotope network using the contemporaneous MESA h_he.net and pp_extras.net networks. They used a total of 31 isotopes (compared to 75 here) including the following: H(1-2), He(3-4), Li(7), Be(7), B(8), C(12-13), N(13-15), O(14-18), F(17-19), Ne(18-22), Mg(22-24), Na(23), Al(27), P(31), and S(32). They used a MESA hard-coded reaction rate for \( 3\alpha \) reactions.
Figure 3. Top panels: Evolution in the H–R diagram of the 0.8 $M_\odot$ CO/He-WD post–merger objects studied here (models A1 through A8). The brown box indicates the observed range of L and $T_{\text{eff}}$ for RCB stars. The letter labels correspond to the following evolutionary phases: A) timescale to reach the RCB phase (taken to be when the model reaches its maximum luminosity), B) timescale it takes a model to exit the RCB box (when $\log T_{\text{eff}} = 3.9$), C) timescale to get to the end of the nearly–constant luminosity post–RCB phase (when $\log L$ starts to decrease) and D) timescale for the model to become a new WD (taken to be when $\log L = -2.0$). Bottom panels: Same as the top panels, but for the H–R diagram evolution of the >0.8 $M_\odot$ CO/He-WD post–merger objects studied here (models B through F).
Figure 4. Evolution of key RCB parameters for the post-merger CO/He-WD models studied here: surface $^7$Li abundance (upper left panel), surface C/O ratio (upper right panel, surface $^{16}$O/$^{18}$O ratio (lower left panel) and surface equatorial rotational velocity $v_{rot}$ (lower right panel).
Such extreme environments such as binary WD mergers present difficulties for stellar evolution routines. We used an entropy relaxation/adjustment to get our model post-merger object. However, Zhang et al. (2014) started with a 4 $M_\odot$ (solar metallicity) model on the ZAMS (always using their custom network even for the stellar evolution), and then gradually started to remove mass (with the MESA relax_mass option). Eventually, their model reaches 0.6 $M_\odot$ CO-WD by removing the rest of the envelope around the core. Then, slow ($10^{-4}$ $M_\odot$ yr$^{-1}$) and fast ($10^{4}$ $M_\odot$ yr$^{-1}$) accretion phases are initiated in which He-WD abundance material accretes onto the 0.6 $M_\odot$ CO-WD remnant. Once this accretion phase ends, the evolution (with physics turned on) begins to get to the RCB phase. The fast accretion used by Zhang et al. is no longer available in MESA.

Zhang et al. (2014) adopted a mass-loss rate, based on Reimers/Blöcker prescriptions that are standard in MESA, throughout the evolution. There is no mass-loss until their models reach the RCB phase. An example is shown in Figure 7 of Zhang et al. We also use Reimers and Blöcker here, but with a smaller efficiency for the Blöcker part. In this manner, the stellar mass remains high (~0.8 $M_\odot$ for the A-models) throughout most of the RCB phase and most of the mass is lost after the star has reached the RCB phase and is on the way out to becoming a hot He Star.

The new models presented here have a larger nuclear network and adopt a different technique to model the merger through entropy relaxation (that is more numerically stable). The models naturally get to the “correct” (i.e., in agreement with observations) mass at RCB phase and include rotation as well. Also, our CO-WD and He-WD abundances are produced using the MESA test-suite directories that are adjusted to make WD models for any choice of network (we use mesa_75.net which has 75 isotopes).

5.2 Abundances and Isotopic Ratios

The RCB stars have a wide-range of unusual characteristics to which the formation scenarios of a merger of a CO/He white dwarf (WD) binary and a final helium-shell flash have been applied. Both scenarios can account for the hydrogen deficiency, stellar absolute brightness, and some of the measured abundances including the excess s-process elements. However, the WD merger can better explain the large masses, long lifetimes, lack of binarity, relatively low C/He ratio, large measured $^{12}$C/$^{13}$C ratio, and greatly enhanced $^{18}$O and $^{19}$F seen in the RCB stars (Asplund et al. 2000; Clayton et al. 2007; Clayton 2012).

There is a wide range of H abundance in the RCB stars.

Figure 5. Abundance profiles of the final WD remnants at the late-stage in the evolution of the CO/He post-merger objects (point “D” in the H–R diagram plots).
There is an anti-correlation between H and Fe abundances in the RCB stars (Asplund et al. 2000) The RCB stars can be roughly divided into a majority group which share similar abundances, and a small minority of stars, which show extreme abundance ratios, particularly Si/Fe and S/Fe (Asplund et al. 2000).

The results of previous studies compared to the observed RCB abundances can be seen in Figure 2 of Longland et al. (2011), Figure 12 of Menon et al. (2013), and Figure 14 of Zhang et al. (2014). The abundances are plotted against [Fe] which in all three previous studies as well as our own find log $\epsilon$(Fe) $\sim$ 7. The measured values of log $\epsilon$(Fe) in 18 RCB stars ranges from 5.5 to 6.9 (Asplund et al. 2000). The Solar value is log $\epsilon$(Fe) = 7.5 (Grevesse & Sauval 1998). The low Fe abundances seen in RCB stars has been ascribed to the progenitor stars being slightly metal poor, to dust condensation and separation from the gas, and to additional nucleosynthesis. The high measured Si/Fe and S/Fe ratios seem to require the latter. But none of these suggestions can explain the Fe abundance (Asplund et al. 2000).

The isotope, $^{18}$O, can be enhanced during H-burning such that the $^{14}$N($\alpha$, $\gamma$)$^{18}$F($^{12}$C) reaction chain leads to enhanced $^{18}$O, if it is not destroyed by $^{16}$O($\alpha$, $\gamma$)$^{22}$Ne (Warner 1967; Lambert 1986; Clayton et al. 2007). Our new MESA modeling produces $^{18}$O/$^{16}$O ratios of ~0.35. The observed ratios in the RCB stars are as high as 20 (the Solar value is 1/500) (Clayton et al. 2007; García-Hernández et al. 2010). Florine is also enhanced by $^{18}$O($p,\gamma$)$^{19}$F (Pandey et al. 2008). This enhancement is seen in the RCB stars.

The models produced by Longland et al. (2011) show enhanced $^{18}$O and $^{19}$F but not as high as observed in some HdC and RCB stars. In Zhang et al. (2014), the models show similar values of $^{18}$O/$^{16}$O to observations, but do not produce enough $^{19}$F to enhance its abundance. Menon et al. (2013) produced models that show enhanced $^{18}$O and $^{19}$F, although the latter is less enhanced than the observations suggest. The stellar structure used in Menon et al. (2013) is less realistic than in the other studies. As seen in Table 5, our new models produce, if anything, too much $^{18}$O as the ratios are a bit higher than observed but do a very good job of reproducing the enhancement of $^{19}$F. None of these studies, including this one, deal with the issue of a significant dredge-up of $^{18}$O during the WD merger which can swamp the amount of $^{18}$O produced (Staff et al. 2012, 2018).

The appearance of Lithium in the atmospheres of some RCB stars has been considered a strong vote for the final-flash scenario. The abundance of Li in the atmosphere of the final-flash star, Sakurai’s object, was actually observed to increase with time (Asplund et al. 1999). Simplistically, one would think that any Li present would be destroyed by the temperatures necessary to produce $^{18}$O. But a few RCB stars, including R CrB, itself, show significant Li in their atmospheres (Rao & Lambert 1996; Asplund et al. 2000; Kipper & Klochkova 2006). Renzini (1990) suggested that the ingestion of the H-rich envelope leads to Li-production through the Cameron-Fowler mechanism ($^3$He($\alpha$, $\gamma$)$^7$Be then $^7$Be($e^−,\nu$)$^7$Li) (Cameron & Fowler 1971).

In the models, the initial $^3$He mass fraction in the CO-WD is of the order of 10$^{−8}$, which is in the agreement with values in Zhang et al. (2014). Longland et al. (2012) connect the observed Li abundance with viewing angle given the non-spherical nature of the post-merger object. They suggest that Li forms through the Cameron-Fowler mechanism in the outer parts of the forming RCB star and at later times resides mainly in a thick accretion disk. Then, if seen side-on, the photosphere of the star is hidden behind the thick accretion disk where you get the enhancement of Li, but when observing RCB stars face-on, radiation of the star itself will dominate the observers measurement and hence, Li abundance measurements will be low. In MESA, since it is a 1D spherically symmetric code, we follow the evolution along the equatorial plane (effectively including the extended corona/disk structure dominated by He-WD material). Li survives in our models because it is convectively transported out to the safer, lower-temperature regions in the corona on time-scales faster than the “destruction” time-scales. Since Li is present in all of our models, it is not clear why Li is present in only a handful of RCB stars. Asplund et al. (2000) suggest that the absence of Li in most RCB stars is due to inefficient production or that the new Li is destroyed by exposure to high temperatures before it can be mixed to the surface.

In general, RCB stars have very large values of $^{12}$C/$^{13}$C. For R CrB, itself, $^{12}$C/$^{13}$C $\geq$40. However, a few RCB stars do have measurable $^{13}$C. V CrA, V854 Cen, VZ Sgr, and UX Ant have measured $^{12}$C/$^{13}$C $<$25 (Rao & Lambert 2008; Hema et al. 2012). In the models of Zhang et al. (2014), the $^{13}$C abundance stays almost perfectly steady. This is because the primary reaction $^{13}$C($^7$He,$n$)$^{16}$O is a neutron reaction and was absent from their network but is included in ours as described above (Asplund et al. 2000). It should also be noted that this is the primary neutron source for s-process, so it must be included in any network used. Then we see that the $^{13}$C burns up rather quickly in the RCB model, and ratios comparable to Zhang’s are difficult to achieve. The final abundance of $^{13}$C in all but one of our MESA models is near zero.

5.3 Lifetimes and Expected Number of RCB Stars

It has been suggested that there is an evolution from He-CO-WD binary mergers → RCB stars → Extreme Helium (EHe) stars → Helium-rich, subdwarf O (He–sdO) stars → Helium-rich O (O(He)) stars → high-mass CO-WD (Jeffery 2008a,b). The total number of RCB stars in the Galaxy is still uncertain. About 150 RCB stars have been identified in the Galaxy and this number is unlikely to grow by more than a factor of two because of recent constructive efforts to find and identify all of the RCB stars (Tisserand 2012; Tisserand et al. 2013, 2018, in preparation). There are only 22 extreme helium (EHe) stars known. Jeffery (2017) recently reported the identification of the first new eHe star in 40 years. There are only 5 low-gravity He–sdO stars and 4 O(He) stars known (Jeffery 2008a).

Population synthesis calculations indicate an RCB birthrate ~10$^{-2}$–10$^{-3}$ yr$^{-1}$ (Han 1998; Nelemans et al. 2001; Tisserand et al. 2013; Zhang et al. 2014; Karakas et al. 2015; Yungelson & Kuranov 2016; Brown et al. 2016). RCB stars are thought to be ~0.8–0.9 M$_\odot$ from pulsation modeling (Saio 2008), and this mass agrees well with the predicted mass of the merger products of a CO- and a He-WD (Han 1998). An actual example of a 0.9 M$_\odot$ WD, which is probably the product of a binary merger, was recently discovered in a binary system with a G dwarf (Schwab et al. 2016b).
Using a value of 0.0018 yr$^{-1}$ for the birthrate of RCB stars (Karakas et al. 2015), we can estimate the number of RCB and EHe stars in the Galaxy by multiplying this value times their typical lifetimes. Table 4 gives the lifetimes as RCB stars ($t_B$) and the lifetimes of the EHe stars ($t_C-t_B$) calculated by our MESA models. Predicted numbers of RCB and EHe stars in the Galaxy using the lifetimes predicted by our MESA models are given in Table 4. There is a very good correspondence between the estimated numbers of RCB and EHe stars in the Galaxy from our MESA models and the actual numbers. Most of the models estimate 200–300 RCB stars and 20–30 EHe stars. The estimated lifetimes of the RCB and EHe stars are $\sim 10^5$ and $\sim 10^4$ yr, respectively. These numbers are also consistent with the idea that RCB and EHe stars are related and are the products of He-/CO-WD mergers.

6 CONCLUSIONS

The new models presented here do at least as well in the matching the observed abundances in HdC and RCB stars as previous studies. Good examples are the abundance of $^{19}$F and $^{18}$O/$^{16}$O where our predictions are in good agreement with the observations. Our new models also reproduce the Li abundances seen in some RCB and the $^{12}$C/$^{13}$C ratios seen in most RCB stars. None of the models including ours reproduce the Fe abundances seen on RCB stars.

The MESA models predict that the ellipsoidal WD merger product becomes spherical in just a few years, and will become an RCB star in less than 1000 yr. The lifetime of an RCB star is $1-2 \times 10^5$ yr governed by the timescale of He burning. During the RCB phase, the stellar mass is reduced from $\sim 0.8$ to $\sim 0.7 M_\odot$. The stars then evolve more quickly as they return to being WDs. They spend $\lesssim 10^4$ yr as EHe stars. When combined with recent population synthesis studies which estimated the merger rate for CO/He WD binaries, these lifetimes predict numbers of RCB and EHe stars which are consistent with the number known in the Galaxy.

If the RCB stars can definitively be shown to be the products of WD mergers then the study of how the RCB stars evolve will lead to a better understanding of other important types of stellar merger events such as Type Ia SNe.

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Figure 6. HR diagram locations of the RCB models (A1 through F) computed in this work during the stage when they reach peak luminosity (at time $t_A$).
### Table 3. Basic properties of the new CO/He-WD post–merger RCB models.

| Model | $M_i$ ($M_\odot$) | $M_{CO}$ ($M_\odot$) | log($R_i/R_\odot$) | $v_{rot,i}/v_{rot,c}$ | log($X_{He,WD}$) | net | $t_A$ (10^5 yr) | $t_B$ (10^3 yr) | $t_C$ (10^5 yr) | $t_D$ (Gyr) | $M_{RCB}$ ($M_\odot$) | $v_{rot,RCB}$ (km s$^{-1}$) |
|-------|------------------|----------------------|-------------------|------------------------|------------------|-----|----------------|----------------|----------------|---------------|----------------------|-------------------------|
| A1    | 0.80             | 0.55                 | -1.12             | 0.2                    | -99              | large | 0.009          | 1.256         | 1.366         | 1.711         | 0.18                 | 0.80                    |
| A2    | 0.80             | 0.55                 | -1.12             | 0.2                    | -9               | large | 0.009          | 1.284         | 1.395         | 1.746         | 0.19                 | 0.80                    |
| A3    | 0.80             | 0.55                 | -1.10             | 0.2                    | -5               | large | 0.009          | 1.270         | 1.382         | 1.755         | 0.16                 | 0.80                    |
| A4    | 0.80             | 0.55                 | -1.10             | 0.0                    | -5               | large | 0.009          | 1.265         | 1.377         | 1.760         | 0.19                 | 0.80                    |
| A5    | 0.80             | 0.55                 | -1.22             | 0.2                    | -5               | reduced | 0.009         | 1.235         | 1.339         | 1.692         | 0.16                 | 0.80                    |
| A6    | 0.80             | 0.55                 | -0.99             | 0.2                    | -5               | large | 0.009          | 1.282         | 1.400         | 1.795         | 0.19                 | 0.80                    |
| A7    | 0.80             | 0.53                 | -1.09             | 0.2                    | -5               | large | 0.012          | 1.720         | 1.846         | 2.260         | 0.16                 | 0.80                    |
| A8    | 0.80             | 0.50                 | -1.05             | 0.2                    | -5               | large | 0.016          | 2.759         | 2.922         | 3.374         | 0.17                 | 0.80                    |
| B     | 0.85             | 0.55                 | -0.94             | 0.2                    | -5               | large | 0.015          | 1.706         | 1.845         | 2.047         | 0.12                 | 0.85                    |
| C     | 0.90             | 0.55                 | -0.90             | 0.2                    | -5               | large | 0.015          | 2.038         | 2.137         | 2.304         | 0.14                 | 0.90                    |
| D     | 0.95             | 0.55                 | -0.94             | 0.2                    | -5               | large | 0.016          | 0.742         | 0.862         | 1.637         | 0.16                 | 0.95                    |
| E     | 1.00             | 0.60                 | -0.80             | 0.2                    | -5               | large | 0.013          | 0.163         | 0.187         | 0.484         | 0.16                 | 0.99                    |
| F     | 1.05             | 0.60                 | -0.74             | 0.2                    | -5               | large | 0.011          | 0.331         | 0.371         | 0.743         | 0.15                 | 1.05                    |

The “large” network choice corresponding to the *mesa_75.net* network and the “reduced” choice corresponding to the *sagb_Nela_NgAll.net*. See § 2 for more details. The timescales (the time in years since the merger event) correspond accordingly to: $t_A$, the timescale to reach the RCB phase (taken to be when the model reaches its maximum luminosity), $t_B$, the timescale it takes the model to exit the RCB box (when log $T_{eff}$ = 3.9), $t_C$, the timescale for the model to reach log $T_{eff}$ = 4.6 covering the hot RCB stars and the eHe (extreme Helium) stars, and $t_D$, the timescale to get to the end of the nearly–constant luminosity post–RCB phase (when log $L$ starts to drop significantly) and (E) timescale for the model to become a new WD (taken to be when log $L$ = -2.0).
Table 4. Lifetimes and Expected Number of RCB Stars

| Model | $t_B$ (10^5 yr) | $t_C$ (10^5 yr) | $t_C - t_B$ (10^5 yr) | $M_{RCB}$ at $t_B$ (M_⊙) | $M_{RCB}^{a}$ (M_⊙) | # RCB$^b$ | # EHe$^b$ |
|-------|----------------|----------------|------------------------|---------------------------|----------------------|----------|----------|
| A1    | 1.256          | 1.366          | 0.11                   | 0.80                      | 0.68                 | 226      | 20       |
| A2    | 1.284          | 1.395          | 0.11                   | 0.80                      | 0.68                 | 231      | 20       |
| A3    | 1.270          | 1.382          | 0.11                   | 0.80                      | 0.68                 | 229      | 20       |
| A4    | 1.265          | 1.377          | 0.11                   | 0.80                      | 0.68                 | 228      | 20       |
| A5    | 1.235          | 1.339          | 0.10                   | 0.80                      | 0.68                 | 222      | 19       |
| A6    | 1.282          | 1.400          | 0.12                   | 0.80                      | 0.68                 | 231      | 21       |
| A7    | 1.720          | 1.846          | 0.13                   | 0.80                      | 0.80                 | 310      | 23       |
| A8    | 2.759          | 2.922          | 0.16                   | 0.80                      | 0.70                 | 497      | 29       |
| B     | 1.706          | 1.845          | 0.14                   | 0.85                      | 0.64                 | 307      | 25       |
| C     | 2.038          | 2.137          | 0.10                   | 0.90                      | 0.66                 | 367      | 18       |
| D     | 0.742          | 0.862          | 0.12                   | 0.95                      | 0.61                 | 134      | 22       |
| E     | 0.163          | 0.187          | 0.02                   | 0.99                      | 0.61                 | 29       | 4        |
| F     | 0.331          | 0.371          | 0.04                   | 1.05                      | 0.63                 | 60       | 7        |

$^a$RCB mass when He-burning ends.

$^b$Predicted numbers of RCB and EHe stars in the Galaxy using the lifetimes predicted by the MESA models. See discussion in Section 5.5.
Table 5. Surface abundances and key abundance ratios of CO/He-WD post–merger models during the RCB phase.

| Model | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | B  | C  | D  | E  | F  | R CrB |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|------|
| H     | 0.0| 0.0| 0.0| 2.4| 3.6| 0.0| 0.0| 0.0| 0.0| 0.0| 0.0| 7.5| 0.0| 6.9  |
| He    | 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5| 11.5 |
| Be    | 0.0| 0.0| 0.0| 2.6| 0.0| 0.0| 0.0| 0.0| 0.0| 2.0| 0.0| 0.0| 2.0| 0.0 |
| Li    | 2.4| 3.3| 3.4| 3.4| 1.2| 3.5| 3.4| 3.5| 3.5| 3.4| 2.6| 3.5| 2.8 |
| C     | 9.5| 9.5| 9.5| 9.5| 9.4| 9.5| 9.4| 9.2| 9.3| 9.3| 9.6| 9.1| 9.2 |
| N     | 5.9| 6.0| 6.0| 6.0| 6.2| 6.1| 6.4| 6.5| 6.6| 6.6| 6.6| 6.6| 8.4 |
| O     | 7.9| 7.9| 7.9| 7.9| 8.0| 8.0| 8.8| 8.6| 8.0| 8.2| 8.2| 8.0| 8.4 | 9.0 |
| F     | 7.3| 7.3| 7.4| 7.4| 4.6| 7.3| 7.2| 7.2| 7.2| 7.3| 6.6| 7.2| 6.9 |
| Ne    | 8.8| 8.8| 8.8| 8.8| 8.8| 8.8| 8.8| 8.8| 8.8| 8.2| 8.8| 8.2| 8.8 | 6.1 |
| Na    | 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8| 6.8 | -   |
| Mg    | 7.5| 7.5| 7.5| 7.5| 7.4| 7.4| 7.4| 7.4| 7.4| 7.4| 7.4| 7.4 | 6.4 |
| Al    | 6.3| 6.3| 6.3| 6.3| 7.9| 6.3| 6.3| 6.3| 6.3| 6.3| 6.3| 6.3 | 5.8 |
| Si    | 7.4| 7.3| 7.3| 7.3| -  | 7.3| 7.3| 7.3| 7.3| 7.3| 7.3 | 7.3 | 7.2 |
| P     | 5.4| 5.4| 5.4| 5.4| -  | 5.4| 5.4| 5.4| 5.4| 5.4| 5.4 | 5.4 | -   |
| S     | 7.0| 7.0| 7.0| 7.0| 7.0| 7.0| 7.0| 7.0| 7.0| 7.0| 7.0 | 7.0 | 6.8 |
| Cl    | 5.1| 5.1| 5.1| 5.1| -  | 5.1| 5.1| 5.1| 5.1| 5.1| 5.1 | 5.1 | -   |
| Ar    | 6.2| 6.4| 6.4| 6.4| 6.4| 6.4| 6.4| 6.4| 6.4| 6.4| 6.4 | 6.4 | 6.4 |
| K     | 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9 | 4.9 | 4.9 |
| Ca    | 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1 | 6.1 | 5.3 |
| Ti    | 4.7| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9| 4.9 | 4.9 | 4.0 |
| Cr    | 5.5| 5.5| 5.5| 5.5| -  | 5.5| 5.5| 5.5| 5.5| 5.5| 5.5 | 5.5 | -   |
| Fe    | 7.3| 7.3| 7.3| 7.3| -  | 7.3| 7.3| 7.3| 7.3| 7.3| 7.3 | 7.3 | 6.5 |
| Ni    | 6.0| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.1| 6.0| 6.0 | 6.1 | 5.5 |
| Zn    | 5.4| 5.4| 5.4| 5.4| -  | 5.4| 5.4| 5.4| 5.4| 5.4| 5.4 | 5.4 | 4.4 |
| ^16O/^18O | 11.5| 10.8| 9.9| 7.2| 6.6| 5.4| 45.2| 13.0| 1.1| 2.4| 1.9 | 3.6 | 2.0 | -1  |
| C/O   | 39.8| 39.8| 39.8| 39.8| 31.6| 25.1| 5.0| 6.3| 15.8| 12.6| 12.6 | 4.0 | 5.0 | 1.6 |

All abundances are in logarithm format. Entries with a dash indicate no available information (elements that are not included in the “reduced” network).

If an abundance is listed as 0.0, it means that it was included in the network but the final abundance, $\log \epsilon(X) < 0$, which is considered to be too small to be measured in observational data.
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