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R CORONAE BOREALIS STARS ARE VIABLE FACTORIES OF PRE-SOLAR GRAINS

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ABSTRACT

We present a new theoretical estimate for the birthrate of R Coronae Borealis (RCB) stars that is in agreement with recent observational data. We find the current Galactic birthrate of RCB stars to be ≈25% of the Galactic rate of Type Ia supernovae, assuming that RCB stars are formed through the merger of carbon–oxygen and helium-rich white dwarfs. Our new RCB birthrate (1.8×10^{-3} yr^{-1}) is a factor of 10 lower than previous theoretical estimates. This results in roughly 180–540 RCB stars in the Galaxy, depending on the RCB lifetime. From the theoretical and observational estimates, we calculate the total dust production from RCB stars and compare this rate to dust production from novae and born-again asymptotic giant branch (AGB) stars. We find that the amount of dust produced by RCB stars is comparable to the amounts produced by novae or born-again post-AGB stars, indicating that these merger objects are a viable source of carbonaceous pre-solar grains in the Galaxy. There are graphite grains with carbon and oxygen isotopic ratios consistent with the observed composition of RCB stars, adding weight to the suggestion that these rare objects are a source of stardust grains.

Key words: binaries: close – ISM: abundances – novae, cataclysmic variables – stars: carbon – white dwarfs

1. INTRODUCTION

R Coronae Borealis (RCB) stars are a rare class of hydrogen-deficient supergiants with atmospheres composed primarily of helium and carbon, where the ratio of carbon atoms to oxygen atoms exceeds unity (C/O > 1; Clayton 1996). They also show abrupt changes in their apparent visual magnitudes. RCB stars are sometimes observed at their maximum light but they have also been observed during their decline phase, in some cases showing sudden declines of up to 8 mag in a few weeks. The star then typically stays faint for a period of several months (Clayton 2012) before eventually recovering back to maximum brightness over a period of several months or longer. The steep decline in brightness is due to dust clouds that are ejected from the star and cover the photosphere when they are in the line of sight. Observations indicate that this dust is made of amorphous carbon grains that cover a range of sizes up to tenths of a micron (García-Hernández et al. 2011, 2013; Jeffers et al. 2012).

The number of RCB stars known in the Galaxy is about 100 (Tisserand et al. 2013), and more are being discovered or will be discovered in ongoing and upcoming surveys of the Galaxy (e.g., *WISE*, *GAIA*, *Euclid*, LSST, and SkyMapper). It is relatively easy to find RCB stars because they are variable and bright, with absolute magnitudes between $-5.2 \leqslant M_V \leqslant -3.4$, where the faint limit can be extended to −2.6 (Tisserand 2012). To identify the object as RCB the typical decline in the light curve has to be identified but the process is simplified because the minimum is very conspicuous in the light curve. Previous estimates suggest that the number of RCB stars in the Galaxy is higher, at over a thousand (e.g., Clayton 2012). In Section 2 we discuss the observations, formation scenarios, and theoretical models of RCB stars in more detail.

Given that the known number of Galactic RCB stars has increased, we want to test whether these objects could be a viable source for producing carbonaceous dust in the Galaxy and if it would be possible to find their nucleosynthesis signature in pre-solar dust grains. Pre-solar grains are minerals that survived the formation of the solar system and can be found in primitive meteorites. Different stellar origins have been proposed for pre-solar grains including asymptotic giant branch (AGB) stars, supernovae, novae, and post-AGB stars. The composition of pre-solar grains varies greatly and indicates many different types of grains and stellar origins (e.g., Zinner 1998, 2014; Lodders & Amari 2005). The bulk of pre-solar grains, both carbon and oxygen-rich types, are associated with the ejecta from supernovae or AGB stars. However, a few grains have been associated with rarer sources such as nova outbursts (Amari et al. 2001a; José et al. 2004) and post-AGB stars (Jadhav et al. 2013). Amari et al. (2001b) briefly discussed RCB stars as a source for silicon carbide (SiC) grains of type A + B, which comprise about 4%–5% of the measured SiC grains to date and are characterized by their carbon isotope ratios, which show $^{12}C/^{13}C < 10$. Amari et al. (2001b) discarded the idea because the majority of carbon isotope measurements for RCB stars are $^{12}C/^{13}C > 40$ as we discuss in Section 2. Furthermore, SiC grains are not seen around RCB stars (Lambert et al. 2001; García-Hernández et al. 2011).

In order to test these ideas we need to know the numbers of RCB stars relative to novae and born-again post-AGB stars (see Section 4). However, of importance for dust production is the dust ejection mass and the lifetime, so we also need estimates of these quantities, which we obtain from theory or observations. This paper is organized as follows. We first provide an overview of the observations and theory of RCB stars in Section 2. In Section 3 we use the results from binary population synthesis models to obtain the number of RCB stars expected from theoretical models where we assume that all RCB stars are formed by double white dwarf (WD) mergers. In Section 4 we take observational and theoretical estimates for the number of RCB stars to provide a dust-production rate. We

also perform a similar calculation for novae and post-AGB stars. We finish in Section 5 with a discussion of our results.

2. THE NATURE AND ORIGIN OF RCB STARS

There are two main competing theories for the formation of RCB stars: (1) the final helium-shell flash scenario or (2) the double degenerate WD merger scenario. The first scenario involves a WD central star of a planetary nebulae undergoing a final thermal pulse, which ignites the helium shell and causes the star to expand to giant dimensions (Clayton 1996). While there is evidence for late thermal pulses in the general population of post-AGB stars (e.g., Sakurai's Object and V605 Aquilae; Duerbeck & Benetti 1996; Asplund et al. 1997; Clayton & de Marco 1997), there are serious problems with this scenario explaining the lifetime of RCB stars. We refer to Table 3 in Clayton (2012) for an overview of the double degenerate versus final flash formation scenarios.

The second scenario states that RCB stars are the merger products of carbon–oxygen (CO) WD and helium-rich WD pairs (Webbink 1984). The progenitor binary system experienced at least one phase of common envelope (CE) evolution (see Section 3). Due to radiation of gravitational waves, the system undergoes orbital decay which causes the two stars to approach each other and finally coalesce. During this merger, the less massive helium WD gets completely disrupted. The matter from the helium WD is believed to form a Keplerian disk that gets assimilated onto the surface of the accretor, where it starts to burn (Jeffery et al. 2011). The remnant of the helium WD might also form an extended envelope around this merging product (Clayton et al. 2011).

RCB stars have pulsation periods on the order of 40–100 days, from which pulsation masses of $\approx$0.8–0.9 $M_{\odot}$ have been derived (Clayton 1996). Models have also shown that the merger of a CO WD and a helium WD is predicted to result in a mass of about $0.96 \pm 0.13\ M_{\odot}$ (Han 1998), which is consistent with the pulsation masses (Clayton 1996; Clayton et al. 2011). It has also been hypothesized that such mergers may lead to thermonuclear explosions such as Type Ia supernovae (SNe Ia), but this remains a topic of investigation (see, e.g., Pakmor et al. 2013; Dan et al. 2014). Han (1998) theoretically predicted the birthrate of RCB stars to be $1.8 \times 10^{-2}\ \mathrm{yr}^{-1}$. In Section 3 we update the predicted RCB birthrate for the Galaxy.

Jeffery et al. (2011) presented surface abundances of RCB stars with respect to evolutionary models that assume that RCB stars are formed by a double degenerate merger of a CO WD and a helium WD. The models were compared to the observations (Asplund et al. 2000; Rao & Lambert 2003, 2008; Pandey et al. 2008), which reveal that RCB stars are enhanced in several elements such as nitrogen, fluorine, sodium, aluminium, phosphorus, silicon, sulfur, and in some neutron capture elements produced by the *slow* neutron capture process. Observations also show unexpectedly low isotopic ratios of $^{16}\mathrm{O}/^{18}\mathrm{O}$ with ratios close to or less than unity (Clayton et al. 2005, 2007; García-Hernández et al. 2010). The ratios of $^{12}\mathrm{C}/^{13}\mathrm{C}$ are generally high, with a lower limit of 30–40 (Cottrell & Lambert 1982; Hema et al. 2012). There are exceptions, including V CrA which has a low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio of $\approx$3–4 (Rao & Lambert 2008), and VZ Sgr with 3–6 (Hema et al. 2012).

The elemental and isotopic abundances of RCB stars are reasonably well matched by merger models, such as those by Jeffery et al. (2011), Longland et al. (2011), and Menon et al. (2013). The models by Jeffery et al. (2011) assume most of the observed surface composition of RCB stars comes from the nucleosynthesis from the AGB phase of the CO WD. Jeffery et al. (2011) identified the need for additional nucleosynthesis during the merger to explain the composition of some elements, such as fluorine, which shows abundances higher than predicted. Menon et al. (2013) reproduce the abundances of C, N, O, and F using a one-dimensional post-merger evolution and nucleosynthesis model based on realistic hydrodynamic merger progenitor models. However, the large Si and S abundances observed in the low metallicity RCB stars are not reproduced, indicating that some high temperature burning at $T \approx 10^9$ K may be occurring.

3. RATES OF RCB STARS FROM POPULATION SYNTHESIS

Theoretical (or extrapolated) estimates for the number of RCB stars range from 200 up to 5700 (Webbink 1984; Lawson et al. 1990; Han 1998; Clayton 2012). To estimate the number of RCB stars expected to currently be in the Galaxy, we calculate theoretical merger rates between helium-rich and CO WDs (hereafter He–CO mergers) using the binary evolution population synthesis code StarTrack (Belczynski et al. 2002, 2008).

Recently, StarTrack input physics have been updated to include a new prescription for accretion of helium-rich material on CO and ONe WDs when stable Roche lobe overflow is encountered (Ruiter et al. 2014). The updated prescription does not affect double WDs that merge upon contact (like RCB progenitors), but does affect binaries involving He–CO systems that do not merge upon contact and thus lead to AM CVn systems, "classical" double-detonation SNe Ia, or other transient events. We use the simulations from the P-MDS model of Ruiter et al. (2014) to calculate the birthrate of RCB stars arising from He–CO mergers. All stars are evolved from the zero-age main sequence (ZAMS), and the evolutionary histories are recorded until $t = 13.7$ Gyr is reached (see Ruiter et al. 2009, Section 2, for a description of initial separations, initial mass function, etc.). For these simulations we have adopted a ZAMS binary fraction of 70% and a burst star formation history, where the burst occurs at $t = 0$. A "burst" simulation is the most powerful since it allows us to easily convolve our event rates (delay times; see below) with any star formation rate of choice to attain a realistic model star formation history.

We note that the delay time distribution (DTD)[5] shape of He–CO mergers relative to CO–CO mergers is qualitatively similar starting from 500 Myr post-starburst, owing to the fact that similar physical processes play a role in determining the post-nuclear burning orbital evolution of double WDs. CO–He mergers do not occur with delay times <500 Myr due to the low-mass nature of the secondary star: a helium–WD progenitor takes longer to complete nuclear evolution than a CO–WD progenitor.

Given the similar DTD shapes beyond 500 Myr, it is reasonable to assume a constant birthrate of RCB to CO–CO mergers at the current epoch ($\sim$11 Gyr). We find the number of He–CO mergers averaged over a Hubble time to be

[5] The delay time distribution (or DTD) is the distribution of events in time—this case, mergers—that occur following a hypothetical burst of star formation at $t = 0$. The DTD shape is a useful tool in quantifying progenitor ages for explosive stellar phenomena, e.g., SNe Ia.

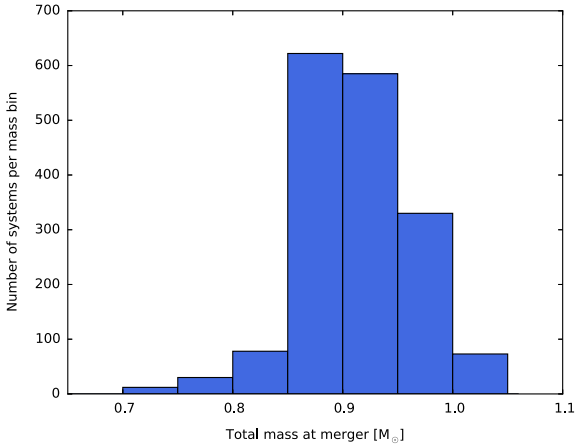

Figure 1. Total mass of RCB systems at the time of merger, grouped into mass bins of 0.05 $M_{\odot}$. We assume all RCB stars are formed through the merger of a CO WD and a helium-rich WD.

$2.7 \times 10^{-14}\,{M_{\odot}}^{-1}\,\mathrm{yr}^{-1}$, where the mass represents the mass born in stars. This value is 25% of our CO–CO merger rate: $1.06 \times 10^{-13}\,{M_{\odot}}^{-1}\,\mathrm{yr}^{-1}$. This rate is remarkably similar to the rate of SNe Ia in Sbc-like galaxies such as the Milky Way: $1.1 \times 10^{-13}\,{M_{\odot}}^{-1}\,\mathrm{yr}^{-1}$, or 7×10^{-3} SNe Ia yr^{-1} as cited by Badenes & Maoz (2012) when adopting a Milky Way stellar mass of $6.4 \pm 0.6 \times 10^{10}\,M_{\odot}$ (McMillan 2011).[6] We adopt this Galactic SN Ia rate in order to extrapolate our RCB population to Galactic numbers: we take the specific rate of He–CO mergers to the observed specific Galactic SN Ia rate, which yields an RCB birthrate of 1.8×10^{-3} RCB stars yr^{-1}.

In Figure 1 we show the distribution of total masses for He–CO mergers over a Hubble time calculated with StarTrack. The mass distribution peaks at $\approx 0.9\,M_{\odot}$, which is consistent with the theoretical estimates of Han (1998) as well as the inferred RCB masses derived from pulsation studies (Clayton 1996; Clayton et al. 2011). We note that in principle, observationally measured RCB masses are likely to be equal to or less than these theoretically predicted RCB "birth" masses, because the merger product will likely lose some mass over time.

We find that RCB stars are formed via three main evolutionary channels, all of which involve one CE event. Factors such as ZAMS mass and initial orbital separation play a role in how soon after star formation the He–CO merger occurs, as well as what the component masses and compositions will be at the time of merger. Two of the evolutionary channels (hereafter channel 1 and channel 2) involve the merger of a CO WD and a "hybrid" helium-rich WD, where the WD has a CO-rich core and a helium-rich mantle. Such HeCO hybrid WDs can be formed in cases where a red giant star is stripped of its envelope during binary interactions, and the helium core only undergoes partial burning (Tutukov & Yungelson 1996). The third evolutionary channel (channel 3) involves the merger of a CO WD and a He WD, the latter of which never underwent any helium core burning.

[6] Note that our simulations are normalized per unit mass born in stars whereas the observational value from Badenes & Maoz (2012) is normalized per unit stellar mass in a given galaxy. We have not attempted to correct for this difference since it unnecessarily introduces uncertainties into our rate. However, changing the normalization technique to more closely match that of observations would lead to a slight increase in our rate, thus we expect even better agreement.

The main difference between channels 1 and 2 is that the ZAMS masses are typically larger by $\sim 1\,M_{\odot}$ for both components in channel 1. Channel 1 CE events occur when the secondary is a red giant, and the WD mergers occur relatively quickly after star formation (within 0.5–1 Gyr). For channel 2, the CE events occur while the secondary is an early AGB star, and the WD mergers occur 1–4 Gyr post-star formation. Channel 3 binary components are slightly less massive both on the ZAMS and at the time of merger. The secondary star is found on the early AGB during the CE phase, and the WD mergers occur >4 Gyr after star formation.

We find the most common formation scenario to be of channel 2 type, followed closely by channel 3. In Figure 2 we show a typical evolution for an RCB star formed via channel 2 from our population synthesis model. Other than birth on the ZAMS and the time of merger (marked i and x in the figure, respectively), we have depicted stages where either a stellar component first evolves off the main sequence (ii, v), initiates a mass transfer phase (iii, vi–viii), or becomes a WD (iv, ix). Over the course of evolution, the binary undergoes a stable mass transfer episode when the primary star is in the Hertzsprung gap, which follows into the red giant phase. After the primary star evolves into a He-rich (hybrid) WD, a CE event occurs while the secondary is an early AGB star. The CE leaves behind a naked helium-burning star in a relatively close orbit ($1\,R_{\odot}$) with the He-rich WD. After the second star becomes a WD, it takes ~800 Myr for the stars to be brought into contact under the influence of gravitational wave radiation.

4. DUST PRODUCTION RATES

An important factor when determining the dust production rates from various sources is not just the number of them at any one time in the Galaxy, but also the amount of dust that each source produces. In this section we present estimates for the number of RCB stars, novae, and born-again post-AGB stars and their dust production rates. Table 1 is a summary of our results, where we highlight the source, the birthrate, the dust mass formed per event, and the dust production rate.

4.1. RCB Stars

In the last decade the observed number of RCB stars in the Galaxy has risen from ~40 (Zaniewski et al. 2005) to 76 (Tisserand et al. 2013). Lawson et al. (1990) extrapolated from the number of known RCB stars at the time to estimate that there are 200–1000 RCB (and cool hydrogen-deficient carbon) stars in the Galaxy, whereas Clayton (2012) extrapolated from the number of known RCB stars in the LMC to arrive at a considerably higher number of 5700 RCB stars.

We perform a similar extrapolation here. Tisserand et al. (2009) find 22 RCB stars in the Magellanic Clouds, with 18 in the Large Magellanic Cloud (LMC) and 4 in the Small Magellanic Cloud (SMC). The Milky Way Galaxy is roughly 10 times more massive than the LMC and 100 times more than the SMC. If we crudely assume that the number of objects scales with galaxy mass (P. R. Wood 2015, private communication), we estimate that there are between 180 and 400 RCB stars in our Galaxy. Only part of the LMC has been searched by MACHO and OGLE, and the number of RCB stars in that galaxy may be significantly higher than 18. Either way, our new numbers are significantly fewer than estimated by Clayton (2012). Our new theoretical birthrate of 1.8×10^{-3} RCB stars

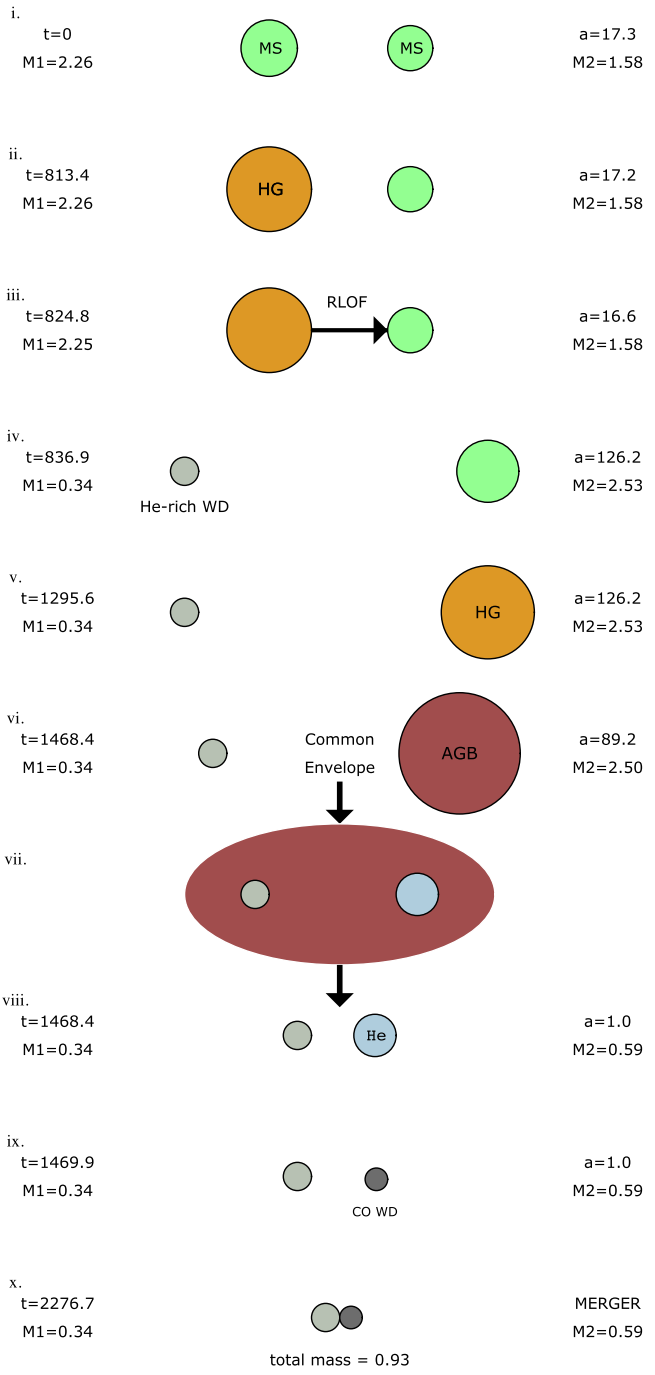

Figure 2. Evolution showing one of the three principle evolutionary channels through which RCB stars are expected to form, as predicted by our StarTrack model. Only the 10 most interesting phases of evolution are shown (see the text). Times are in Myr since the birth on the ZAMS, separations (a) are in $R_\odot$, and masses ($M1$, $M2$) are in $M_\odot$. The phase of stellar evolution prior to WD formation is denoted as follows: MS—main sequence, HG—Hertzsprung gap, AGB—asymptotic giant branch, He—(stripped envelope) helium-burning star.

yr^{-1}, a factor of 10 lower than predicted by Han (1998), results in ≈180–540 Galactic sources when taking RCB lifetimes between (1–3) $\times$ 10^5 years. This theoretical estimate is in good agreement with our extrapolated number of RCB stars.

Observational estimates of the amount of carbon-rich dust ejected from RCB stars ranges from $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ (Clayton et al. 1992) to $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ (Feast 1986). These numbers are consistent with the latest observational estimate of 9×10^{-7} $M_\odot\,\mathrm{yr}^{-1}$ from Clayton et al. (2011) and Jeffers et al. (2012). In Table 1 we calculate our dust-production rates using $10^{-6}\,M_\odot$ yr^{-1}; choosing the lower limit of $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ would lower our dust production rates by an order of magnitude. Furthermore, we have assumed that all RCB stars produce the same amount of carbon-rich dust, which may not always be the case.

Taking the observed number of RCB stars in the Galaxy to be ∼100 we obtain a dust production rate of $M_{\rm dust}^{\rm RCB} \approx 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$, assuming a dust mass-loss rate of $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$. Using our newly calculated RCB birthrate, adopting an upper limit for the RCB lifetime of 3×10^5 years, and again assuming a dust mass-loss rate of $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$, our best theoretical estimate yields a dust production rate of $M_{\rm dust}^{\rm RCB} \approx 5.4 \times 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$. In order to find a hard upper limit, we take the theoretical birthrate from Han (1998) of $1.8 \times 10^{-2}\,\mathrm{yr}^{-1}$ and an RCB lifetime of 3×10^5 years, which results in 5400 RCB stars. This yields a dust production rate of $5 \times 10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$. Our range of dust-production rates for RCB stars is summarized in Table 1.

One substantial uncertainty in this estimate is the lifetime of RCB stars. That there are only about 100 found out of the ≈200–5000 theoretically predicted may simply reflect a shorter lifetime for the RCB phase than estimated by, e.g., Clayton (2012).

4.2. Novae

We now compare these rates to the dust production expected from novae. Similar to the situation for RCB stars, the frequencies and mass-loss rates for novae cover a wide range. Galactic nova rate estimates have yielded numbers from $10\,\mathrm{yr}^{-1}$ (Ciardullo et al. 1990) to $\approx 100\,\mathrm{yr}^{-1}$ (Liller & Mayer 1987; Shafter 1997). Most estimates are somewhere in the middle of this range at values of around $\approx$30–40 yr^{-1} (Hatano et al. 1997; Nelson et al. 2004; Darnley et al. 2006). Nova rates are better constrained in M31 than in the Milky Way, with an estimate of $65\,\mathrm{yr}^{-1}$ (Darnley et al. 2006).

The error estimates are highly uncertain. We take an upper limit of $100\,\mathrm{yr}^{-1}$ to ensure that we are not underestimating dust production from novae. Typical dust formation masses span a wide range from $10^{-10}\,M_\odot$ to an upper limit of $\approx 10^{-5}\,M_\odot$, where most of the dust produced by novae is carbon-rich (Gehrz et al. 1998). We will take the lower and upper limits (see Table 1), which yield nova dust production rates of $M_{\rm dust}^{\rm novae} \approx 10^{-8}$–$10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$.

Note that nova explosions do not always result in detectable dust production, with 3 out of the 25 sources in Gehrz et al. (1998) showing no dust, and another 4 with no information on the types of dust formed.

4.3. Born-again Post-AGB Stars

There is no expected dust production associated with the post-AGB phase because the stars are too hot to form dust (van Winckel 2003). The dust around post-AGB stars is recycled AGB dust. The late and very late thermal pulse post-AGB stars are different: these objects are born-again giant stars such as Sakurai's Object that may produce their own, C-rich dust (Duerbeck & Benetti 1996). Born-again stars have been considered a source of pre-solar grains (Jadhav et al. 2008, 2013). Few born-again stars have been studied so we do not have a good estimate of the observed mass-loss rates.

Table 1
Birthrates, Expelled Dust Mass, and Dust Production from RCB Stars, Novae, and Born-again Post-AGB Stars in the Galaxy

Source	Birthrate (yr^{-1})	Dust Expelled Per Event ($M_\odot$)	Dust Production Rate ($M_\odot$ yr^{-1})
R Coronae Borealis stars	1.8×10^{-3}	$(0.1–1) \times 10^{-6}$	$(1–50) \times 10^{-4}$
Novae explosions	$(1–10) \times 10^{1}$	10^{-10}–10^{-5}	10^{-8}–10^{-3}
Born-again post-AGB stars	$(0.63–28) \times 10^{-1}$	4×10^{-6}	$(7.5–34) \times 10^{-6}$

Sakurai's Object is the best studied and van Hoof et al. (2007) calculate a lower limit to the mass of the total ejecta to be $6 \times 10^{-4}\,M_\odot$. The most recent estimate gives a dust mass of $4 \times 10^{-6}\,M_\odot$ (A. Zijlstra 2015, private communication). We assume that each born-again AGB star ejects the same amount of dust as Sakurai's Object over the born-again lifetime. The lifetime of a born-again AGB star is approximately that of a thermal pulse ($\tau_{\rm TP} \approx 10^2$ years), giving an average dust mass-loss rate of $4 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$.

While we do not know the number of born-again AGB stars in the Galaxy, we can estimate how many there are using the number of post-AGB stars. Kamath et al. (2014) and Kamath et al. (2015) recently estimated the number of post-AGB stars in the LMC and SMC to be 75 and 34, respectively. These numbers include both single and binary post-AGB stars, and they derive a combined post-AGB lifetime of $\approx 5 \times 10^3$ years, consistent with lifetimes from evolutionary tracks (Vassiliadis & Wood 1994). If we scale the number of post-AGB stars in the Magellanic Clouds to the Galaxy like we did for RCB stars we obtain between 750 and 3400 post-AGB stars.

To calculate the birthrate of post-AGB stars in the Galaxy we require a lifetime that has been theoretically estimated to be $\approx 10^3$–10^4 (Vassiliadis & Wood 1994). We obtain 0.18–3.4 yr^{-1}. The lower values are consistent with estimates of planetary nebula birthrates of about 0.5 yr^{-1} by Zijlstra & Pottasch (1991), whereas Moe & De Marco (2006) find a higher value of 1.7 ± 0.3 yr^{-1} for the entire Milky Way. Moe & De Marco (2006) also give a post-AGB birthrate of 2.2 ± 0.5 yr^{-1}, which is estimated to be 90% of the WD birthrate. The post-AGB birthrate from Moe & De Marco (2006) is closer to our upper estimate of 3 yr^{-1}.

Iben (1984) and Renzini (1982) estimate that 10%–25% of all stars that leave the AGB experience a late thermal pulse. Using our new extrapolation for the number of post-AGB stars in the Galaxy, and assuming that 25% of all post-AGB stars experience a late thermal pulse, we obtain between 188 and 850 born-again AGB stars. Using the expelled mass provided in Table 1 we estimate that born-AGB stars produce $M_{\rm dust}^{\rm born\text{-}again} \approx (7.5–34) \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$.

Assuming a lifetime of 10^2 years for a late thermal pulse allows us to estimate the birthrate of born-again AGB stars to be between 1.9–8.5 yr^{-1}. The upper limit seems unreasonably high. Either we have overestimated the number of post-AGB stars or we have underestimated the lifetime of a late helium-shell flash. The low-mass ($\lesssim 2\,M_\odot$) AGB models of Karakas (2014) spend a few times 10^2 years with a convective He-shell. In Table 1 we assume the timescale of a He-shell flash is 300 years, which gives birthrates of 0.63–2.83 born-again post-AGB stars per year. These birthrates are much more reasonable when compared to the post-AGB birthrate from Moe & De Marco (2006).

Unlike RCB stars, not all of the dust from born-again AGB stars may be carbon-rich, but this is yet to be determined. Reducing the number of post-AGB stars that experience late thermal pulses to 10% lowers the number of stars to 75–340 and the amount of dust produced to $(3–14) \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$. Note that increasing the duration of the thermal pulse to 300 years will decrease the dust mass-loss rate.

5. DISCUSSION AND CONCLUDING REMARKS

We present a new theoretical birthrate for RCB stars of 1.8×10^{-3} yr^{-1}, a factor of 10 lower than the previous estimate by Han (1998). We note that in the simulations of Han (1998), it was assumed that all double degenerates that reach contact will eventually merge (Z. Han 2015, private communication). Therefore, one would naturally expect a higher RCB birthrate than we obtain here, since in StarTrack we do not assume all double degenerates merge. Whether a double degenerate binary merges depends on the adopted mass transfer stability criteria for a given model (see Toonen et al. 2014) and will strongly impact the resulting merger rates. Shen (2015) recently suggested that every interacting double WD binary may merge, which would increase the predicted number of RCB stars. Using our new birthrate we predict that there should be roughly 180–540 RCB stars in the Galaxy. We also estimate the number of RCB stars independently from the number known in the Magellanic Clouds, and arrive at an estimate consistent with our new theoretical predictions.

We calculate the dust production rate from RCB stars, novae, and born-again post-AGB stars with our results presented in Table 1. We show that the dust mass-loss rate from RCB stars is comparable to or higher than novae and born-again post-AGB stars, even when accounting for the large uncertainty in the numbers of these objects in the Galaxy today. Our simple arguments, along with updated observational and theoretical estimates for the numbers of RCB stars in the Galaxy, show that RCB stars are a viable source of carbonaceous pre-solar grains.

Are there any pre-solar grains that show the chemical signature of RCB stars? Recall that RCB stars have high C/O ratios, $^{12}C/^{13}C$ ratios $\gtrsim 40$, and $^{16}O/^{18}O$ ratios between ≈ 0.2 and 20 (Clayton et al. 2007; García-Hernández et al. 2010), and some show a signature of heavy element production by the *s* process (Jeffery et al. 2011; Menon et al. 2013). García-Hernández et al. (2010) also attempt to derive $^{14}N/^{15}N$ ratios but only provide lower limits due to the non-detection of the $^{12}C^{15}N$ line.

The pre-solar grain database from Hynes & Gyngard (2009) has a comprehensive list of all the measured isotopic and elemental compositions of pre-solar grains from the literature. Here we focus on the graphite grains as these likely formed in a highly ^{12}C-rich environment. Furthermore, silicon carbide features have not been detected around any RCB stars to date (García-Hernández et al. 2011, 2013). Amari et al. (1993) observe that graphite grains with the largest ^{18}O excesses also have the highest $^{12}C/^{13}C$ ratios. These could be associated with an RCB origin. There are roughly 1800 graphite grains with carbon isotopic ratios that match RCB stars but only about 10

grains with measured $^{16}O/^{18}O$ ratios <25. All 10 grains have large $^{12}C/^{13}C$ ratios ($\geqslant$160) and high $^{26}Al/^{27}Al$ ratios $\geqslant$0.028, consistent with hydrogen burning. Menon et al. (2013) predict that Al can be produced, depending on the interplay between the temperature and the burning timescale, but they do not provide predictions for ^{26}Al in particular. They also note that both Si and Ca are observed to be enhanced in RCB stars but their models do not reproduce these abundances. Neutron captures also occur in the models by Menon et al. (2013), which could explain the excesses of $^{29,30}Si$ observed in the graphite grains. Unfortunately they do not provide isotopic predictions for comparison to the grain data. Future work is needed to further explore the viability of whether the grains with excesses in ^{18}O could indeed have originated from RCB stars.

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REFERENCES

Amari, S., Gao, X., Nittler, L. R., et al. 2001a, ApJ, 551, 1065
Amari, S., Hoppe, P., Zinner, E., & Lewis, R. S. 1993, Natur, 365, 806
Amari, S., Nittler, L. R., Zinner, E., Lodders, K., & Lewis, R. S. 2001b, ApJ, 559, 463
Asplund, M., Gustafsson, B., Lambert, D. L., & Kameswara Rao, N. 1997, A&A, 321, L17
Asplund, M., Gustafsson, B., Lambert, D. L., & Kameswara Rao, N. 2000, A&A, 353, 287
Badenes, C., & Maoz, D. 2012, ApJL, 749, L11
Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223
Ciardullo, R., Tamblyn, P., Jacoby, G. H., Ford, H. C., & Williams, R. E. 1990, AJ, 99, 1079
Clayton, G. C. 1996, PASP, 108, 225
Clayton, G. C. 2012, JAVSO, 40, 539
Clayton, G. C., & De Marco, O. 1997, AJ, 114, 2679
Clayton, G. C., Geballe, T. R., Herwig, F., Fryer, C., & Asplund, M. 2007, ApJ, 662, 1220
Clayton, G. C., Herwig, F., Geballe, T. R., et al. 2005, ApJL, 623, L141
Clayton, G. C., Sugerman, B. E. K., Stanford, S. A., et al. 2011, ApJ, 743, 44
Clayton, G. C., Whitney, B. A., Stanford, S. A., & Drilling, J. S. 1992, ApJ, 397, 652
Cottrell, P. L., & Lambert, D. L. 1982, ApJ, 261, 595
Dan, M., Rosswog, S., Brüggen, M., & Podsiadlowski, P. 2014, MNRAS, 438, 14
Darnley, M. J., Bode, M. F., Kerins, E., et al. 2006, MNRAS, 369, 257
Duerbeck, H. W., & Benetti, S. 1996, ApJL, 468, L111
Feast, M. W. 1986, in IAU Coll. 87: Hydrogen Deficient Stars and Related Objects, Astrophysics and Space Science Library, Vol. 128, ed. K. Hunger, D. Schoenberner & N. K. Rao (Dordrecht: Reidel), 151
García-Hernández, D. A., Lambert, D. L., Kameswara Rao, N., Hinkle, K. H., & Eriksson, K. 2010, ApJ, 714, 144
García-Hernández, D. A., Rao, N. K., & Lambert, D. L. 2011, ApJ, 739, 37
García-Hernández, D. A., Rao, N. K., & Lambert, D. L. 2013, ApJ, 773, 107
Gehrz, R. D., Truran, J. W., Williams, R. E., & Starrfield, S. 1998, PASP, 110, 3
Han, Z. 1998, MNRAS, 296, 1019
Hatano, K., Branch, D., Fisher, A., & Starrfield, S. 1997, MNRAS, 290, 113
Hema, B. P., Pandey, G., & Lambert, D. L. 2012, ApJ, 747, 102
Hynes, K. M., & Gyngard, F. 2009, LPSC, 40, 1198
Iben, I., Jr. 1984, ApJ, 277, 333
Jadhav, M., Amari, S., Marhas, K. K., et al. 2008, ApJ, 682, 1479
Jadhav, M., Pignatari, M., Herwig, F., et al. 2013, ApJL, 777, L27
Jeffers, S. V., Min, M., Waters, L. B. F. M., et al. 2012, A&A, 539, A56
Jeffery, C. S., Karakas, A. I., & Saio, H. 2011, MNRAS, 414, 3599
José, J., Hernanz, M., Amari, S., Lodders, K., & Zinner, E. 2004, ApJ, 612, 414
Kamath, D., Wood, P. R., & van Winckel, H. 2014, MNRAS, 439, 2211
Kamath, D., Wood, P. R., & van Winckel, H. 2015, MNRAS, in press
Karakas, A. I. 2014, MNRAS, 445, 347
Lambert, D. L., Rao, N. K., Pandey, G., & Ivans, I. I. 2001, ApJ, 555, 925
Lawson, W. A., Cottrell, P. L., Kilmartin, P. M., & Gilmore, A. C. 1990, MNRAS, 247, 91
Liller, W., & Mayer, B. 1987, PASP, 99, 606
Lodders, K., & Amari, S. 2005, ChEG, 65, 93
Longland, R., Lorén-Aguilar, P., José, J., et al. 2011, ApJL, 737, L34
McMillan, P. J. 2011, MNRAS, 414, 2446
Menon, A., Herwig, F., Denissenkov, P. A., et al. 2013, ApJ, 772, 59
Moe, M., & De Marco, O. 2006, ApJ, 650, 916
Nelson, L. A., MacCannell, K. A., & Dubeau, E. 2004, ApJ, 602, 938
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJL, 770, L8
Pandey, G., Lambert, D. L., & Rao, N. K. 2008, ApJ, 674, 1068
Rao, N. K., & Lambert, D. L. 2003, PASP, 115, 1304
Rao, N. K., & Lambert, D. L. 2008, MNRAS, 384, 477
Renzini, A. 1982, in IAU Symp. 99, Wolf-Rayet Stars: Observations, Physics, Evolution, ed. C. W. H. De Loore & A. J. Willis (Dordrecht: Reidel), 413
Ruiter, A. J., Belczynski, K., & Fryer, C. 2009, ApJ, 699, 2026
Ruiter, A. J., Belczynski, K., Sim, S. A., Seitenzahl, I. R., & Kwiatkowski, D. 2014, MNRAS, 440, L101
Shafter, A. W. 1997, ApJ, 487, 226
Shen, K. J. 2015, ApJL, 805, L6
Tisserand, P. 2012, A&A, 539, A51
Tisserand, P., Clayton, G. C., Welch, D. L., et al. 2013, A&A, 551, A77
Tisserand, P., Wood, P. R., Marquette, J. B., et al. 2009, A&A, 501, 985
Toonen, S., Claeys, J. S. W., Mennekens, N., & Ruiter, A. J. 2014, A&A, 562, A14
Tutukov, A., & Yungelson, L. 1996, MNRAS, 280, 1035
van Hoof, P. A. M., Hajduk, M., Zijlstra, A. A., et al. 2007, A&A, 471, L9
van Winckel, H. 2003, ARA&A, 41, 391
Vassiliadis, E., & Wood, P. R. 1994, ApJS, 92, 125
Webbink, R. F. 1984, ApJ, 277, 355
Zaniewski, A., Clayton, G. C., Welch, D. L., et al. 2005, AJ, 130, 2293
Zijlstra, A. A., & Pottasch, S. R. 1991, A&A, 243, 478
Zinner, E. 1998, AREPS, 26, 147
Zinner, E. 2014, ed. A. M. Davis in Microphysics of Cosmic Plasmas (Amsterdam: Elsevier), 181