What Are the R Coronae Borealis Stars?

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Abstract The R Coronae Borealis (RCB) stars are rare hydrogen-deficient, carbon-rich, supergiants, best known for their spectacular declines in brightness at irregular intervals. Efforts to discover more RCB stars have more than doubled the number known in the last few years and they appear to be members of an old, bulge population. Two evolutionary scenarios have been suggested for producing an RCB star, a double degenerate merger of two white dwarfs, or a final helium shell flash in a planetary nebula central star. The evidence pointing toward one or the other is somewhat contradictory, but the discovery that RCB stars have large amounts of ^{18}O has tilted the scales towards the merger scenario. If the RCB stars are the product of white dwarf mergers, this would be a very exciting result since RCB stars would then be low-mass analogs of type Ia supernovae. The predicted number of RCB stars in the Galaxy is consistent with the predicted number of He/CO WD mergers. But, so far, only about sixty-five of the predicted 5,000 RCB stars in the Galaxy have been discovered. The mystery has yet to be solved.

1. Introduction

R Coronae Borealis (R CrB) was one of the first variable stars identified and studied. It received the “R” which designates it as the first variable star discovered in the constellation Corona Borealis. Its brightness variations have been monitored since its discovery over 200 years ago (Pigott and Englefield 1797). Early spectra showed variations in the strengths of the Swan bands of C_2 (Espin 1890) and evidence of the absence of hydrogen was soon detected (Ludendorff 1906; Cannon and Pickering 1912), although not confirmed until later (Berman 1935; Bidelman 1953). In addition, the explanation behind the large declines in brightness, the production of thick clouds of carbon dust, was deduced very early on (Loreta 1935; O’Keefe 1939). But the stellar evolution that produced R CrB remains mysterious.

The R Coronae Borealis (RCB) stars are a small group of carbon-rich supergiants. About sixty-five RCB stars are known in the Galaxy and over twenty in the Magellanic Clouds. Their defining characteristics are hydrogen deficiency and unusual variability. RCB stars undergo massive declines of up to 8 magnitudes due to the formation of carbon dust at irregular intervals. 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). There are also six hydrogen-deficient carbon (HdC) stars that are RCB stars spectroscopically, but do not show declines in brightness or IR excesses (Warner 1967; Goswami *et al.* 2010; Tisserand 2012).

Two scenarios have been proposed for the origin of an RCB star: the double degenerate (DD) and the final helium-shell flash (FF) models (Iben *et al.* 1996; Saio and Jeffery 2002). The former involves the merger of a CO- and a He-white dwarf (WD) (Webbink 1984). In the latter case, thought to occur in 20% of all AGB stars, a star evolving into a planetary nebula (PN) central star undergoes a helium flash and expands to supergiant size (Fujimoto 1977). Three stars (Sakurai's Object, V605 Aql, and FG Sge) have been observed to undergo FF outbursts that transformed them from hot evolved PN central stars into cool giants with spectroscopic properties similar to RCB stars (Clayton and De Marco 1997; Gonzalez *et al.* 1998; Asplund *et al.* 1998, 1999, 2000; Clayton *et al.* 2006).

Recent observations and population synthesis models imply that there are a significant number of close DD binaries in the Galaxy. A majority of binaries, close enough to interact sometime during their evolution, will end up as DD systems where both stars are WDs (Nelemans *et al.* 2005; Badenes and Maoz 2012). If the resulting DD system has a short enough period ($\lesssim$ 0.2 hr) it will enter a phase of mass-transfer and may merge in less than a Hubble time due to the loss of energy due to gravitational radiation. This may result in a SN Ia explosion if the total mass of the DD system is greater than the Chandrasekhar limit, or in RCB and HdC stars if the mass is lower than this limit (Webbink 1984; Yungelson *et al.* 1994).

Recently, the surprising discovery was made that RCB stars have $^{16}O/^{18}O$ ratios that are orders of magnitude lower than for any other known stars (Clayton *et al.* 2005, 2007; García-Hernández *et al.* 2010). Greatly enhanced ^{18}O is evident in every HdC and RCB that has been measured and is cool enough to have detectable CO bands. IR spectra of Sakurai's Object, obtained when it had strong CO overtone bands, showed no evidence for ^{18}O (Geballe *et al.* 2002). Therefore, Sakurai's Object and the other FF stars on the one hand, and most of the RCB and HdC stars on the other hand, are likely to be stars with different origins. No overproduction of ^{18}O is expected in the FF scenario but in a DD merger, partial helium burning may take place leading to enhanced ^{18}O (Clayton *et al.* 2007). This strongly suggests that the RCB stars are the results of mergers of close WD binary systems. These discoveries are important clues which will help to distinguish between the proposed DD and FF evolutionary pathways of HdC and RCB stars.

There have been three conferences devoted to hydrogen-deficient stars held in 1985, 1995, and 2007. The proceedings of these conferences contain many papers concerning the RCB stars and related objects (Hunger *et al.* 1986; Jeffery and Heber 1996; Werner and Rauch 2008). The last general review of the RCB stars appeared sixteen years ago (Clayton 1996). Since then, the number of RCB stars known has more than doubled and about 250 papers have been written. This review will concentrate on the advances in our knowledge of RCB stars that have been made since 1996.

2. How to identify an RCB star

2.1. The light curve

As seen in Figure 1, the RCB light curve is unique. No other type of star displays such wild, irregular, large amplitude variations (see, for example, Payne-Gaposchkin and Gaposchkin 1938; Clayton 1996).

- An RCB star will stay at uniform brightness at maximum for months or years. Then, there will be a sudden drop in brightness of more than three magnitudes taking a few days or weeks, followed by a recovery to maximum light, which is typically slower, taking months or years. Notice the latest decline of R CrB, itself, shown in Figure 1. After over 1,000 days at maximum, it plunged seven magnitudes in less than 100 days and has stayed in a deep decline for almost 2,000 days.

- The characteristic time between declines in RCB stars is typically about 1,000 days, but there is a wide range in activity among the RCB stars (Feast 1986; Jurcsik 1996).

- The stars also show regular or semiregular pulsations with a small amplitude ($\Delta V \lesssim 0.1$ magnitude) and periods of 40–100 days (see, for example, Lawson *et al.* 1990; Percy *et al.* 2004).

2.2. The spectrum

Figure 2 shows the maximum light spectra of the RCB stars, S Aps ($T_{eff} \sim 5000$ K) and RY Sgr ($T_{eff} \sim 7000$ K), and the carbon star, RV Sct.

- The RCB spectra are characterized by weak or absent hydrogen Balmer lines, and weak or absent CH λ4300 band. But, there is a wide range of hydrogen abundance in the RCB stars. For example, V854 Cen shows significant hydrogen in its spectrum (Kilkenny and Marang 1989; Lawson and Cottrell 1989). There is an anti-correlation between hydrogen and metallicity in the RCB stars (Asplund et al. 2000).

- The RCB star spectrum contains many lines of neutral atomic carbon. The cooler stars ($T_{eff} < 6000$ K) show strong absorption bands of C_2 and CN, as seen in S Aps, but in the warmer stars, such as RY Sgr, these bands are weak or absent. A warm RCB star can appear almost featureless in the visible, having no Balmer lines, helium lines, or molecular bands.

- In most, but not all, RCB stars, the abundance of ^{13}C is very small. This can be seen in the two wavelength sections shown in Figure 2. The isotopic Swan bands of C_2 are separated in wavelength, so the spectra can be inspected to see the relative strengths of ^{12}C^{12}*C* λ4737.0 and ^{12}C^{13}C λ4744.0 in the blue, and ^{12}C^{12}C λλ6059, 6122, 6191, and ^{12}C^{13}C λλ6100, 6168 in the red (Lloyd Evans *et al.* 1991; Kilkenny *et al.* 1992; Alcock *et al.* 2001).

- The strength of the CN λ6206 band compared to the ^{12}C^{12}C λ6191 band is relatively weak in the RCB stars compared to the carbon stars (Lloyd Evans *et al.* 1991; Morgan *et al.* 2003).

The description above applies to RCB spectra at or near maximum light. In deep declines, a rich narrow-line emission spectrum appears consisting of lines of neutral and singly ionized metals, and a few broad lines including Ca II H and K, and the Na I D lines (Payne-Gaposchkin 1963; Alexander *et al.* 1972; Feast 1975). The decline spectrum is described in detail in Clayton (1996). More recent papers detailing the decline spectra of RCB stars include Rao and Lambert (1997), Rao *et al.* (1999), Clayton *et al.* (1999a), Skuljan and Cottrell (1999), Lawson *et al.* (1999), Rao and Lambert (2000), Clayton and Ayres (2001), Kipper (2001), Skuljan and Cottrell (2002a, 2002b), Rao *et al.* (2004), Kipper and Klochkova (2006b), and Rao *et al.* (2006). A small subclass of RCB stars is much hotter with effective temperatures of about 20,000 K. See De Marco *et al.* (2002, and references therein) for a description of their spectra.

2.3. Infrared emission

- Every RCB star has an IR excess, from the K-band to far-IR wavelengths due to warm circumstellar dust ($T_{eff} \sim 400$–1000 K) (Feast *et al.* 1997). Most Galactic RCB stars have been detected by 2MASS, IRAS, AKARI, and WISE (see, for example, Walker 1985; Tisserand 2012). Recently, two RCB stars, R CrB and HV 2671, were detected out to 500 μm by the Herschel Space Observatory (Clayton *et al.* 2011a, 2011b).

- The mid-IR spectra of RCB stars are mostly featureless since there are usually no silicate, SiC, or polycyclic aromatic hydrocarbon (PAH) features present (Lambert *et al.* 2001; Kraemer *et al.* 2005; García-Hernández *et al.* 2011a). However, V854 Cen and DY Cen do show emission features attributed to PAHs and C_{60} (Lambert *et al.* 2001; García-Hernández *et al.* 2011b).

3. The population of RCB stars

Clayton (1996) listed thirty-four Galactic and three LMC RCB stars. Since then, the number of confirmed RCB stars has almost doubled in the Galaxy, and greatly increased to over twenty in the Magellanic Clouds. Tables 1 and 2 list all the RCB and HdC stars known in the Galaxy and the Magellanic Clouds which have been confirmed by spectral classification, light curve behavior, and IR excesses. V2331 Sgr is a strong new candidate from its light curve and IR excess, but does not have a spectrum (Tisserand *et al.* 2012). EROS2-LMC-RCB-6, and OGLE-GC-RCB-2 are also good candidates that do not have spectra (Tisserand *et al.* 2009, 2011; Tisserand 2012). V391 Sct was originally classified as a dwarf nova that brightened from V = 17 to 13 magnitudes. But Brian Skiff (2010) suggested that this star might be an RCB star based on brightness variations seen on a few plates. This is supported by the ASAS-RCB-3 light curve which, while it does not show any declines, reveals that the star is normally V = 13, not V = 17. Its spectrum shows it to be a warm RCB star, very similar to RY Sgr and it has an IR excess (Tisserand *et al.* 2012). A strong spectroscopic candidate, KDM 6546, has no light curve (Morgan *et al.* 2003). It was previously classified as a CH star (Hartwick and Cowley 1988). Three stars included in the RCB list of Clayton (1996), GM Ser, V1773 Oph, and V1405 Cyg, had not been spectroscopically confirmed (Kilkenny 1997). GM Ser is not an RCB star (Tisserand *et al.* 2012). The other two stars are still unconfirmed and so are not included in Table 1. Another star, MACHO 118.18666.100, previously identified as an RCB star (Zaniewski *et al.* 2005), has been shown to be misidentified (Tisserand *et al.* 2008).

There are also four hot (15,000–20,000 K) RCB stars known. One, HV 2671, was recently discovered in the LMC (Alcock *et al.* 1996). The three Galactic stars are, V348 Sgr, MV Sgr, and DY Cen. These stars are all hydrogen-deficient, carbon-rich stars, and have RCB-type light curves (Clayton 1996; De Marco *et al.* 2002; Clayton *et al.* 2011b). DY Cen and MV Sgr have the typical RCB-star large helium abundances, but V348 Sgr and HV 2671 are in general agreement with a born-again post-AGB evolution, and are similar to Wolf-Rayet central stars of PNe with carbon and helium being close to equal in abundance (De Marco *et al.* 2002). So DY Cen and MV Sgr seem to be related to the cooler RCB stars, but V348 Sgr and HV 2671 may be [WC] central stars. The six known HdC stars are also listed in Table 1. One of these stars, HD 175893, may be an RCB star since it has an IR excess (Tisserand 2012). However, no declines have been observed for this star.

There is a small group of stars, of which DY Per is the prototype, that resemble the RCB stars (Alksnis 1994). These stars have very deep declines at irregular intervals, but the rate of fading is very slow and the shape of the declines is much more symmetrical than the typical RCB decline (Alcock *et al.* 2001). DY Per is significantly cooler ($T_{eff} \sim 3500$ K) than the coolest RCB stars (Keenan and Barnbaum 1997).

Both of the evolutionary theories, the DD and the FF scenarios, suggest that the RCB stars are an old population (Clayton 1996). The distribution on the sky and radial velocities of the RCB stars tend toward those of the bulge population (Drilling 1986; Cottrell and Lawson 1998; Zaniewski *et al.* 2005). Tisserand *et al.* (2008) determined that the RCB stars follow a disk-like distribution inside the Bulge with a scale-height <250 pc. The distribution of the RCB stars on the sky, including the new expanded sample from Table 1, is plotted in Figure 3. There is no direct measurement of the distance to any Galactic RCB star (Alcock *et al.* 1996). But, now that significant numbers of RCB stars have been identified in the LMC, whose distance is well known, the absolute brightness of the RCB stars has been determined to range from $M_V = -3$ for stars with $T_{\mathrm{eff}} \sim 5000$ K to -5 for stars with $T_{\mathrm{eff}} \sim 7000$ K (Feast 1979; Alcock *et al.* 2001). HV 2671, the hot RCB star in the LMC, has $M_V \sim -3$ (Alcock *et al.* 2001; Tisserand *et al.* 2009).

Webbink (1984) suggested that the DD scenario would result in a population of about 1,000 Galactic RCB stars. Iben *et al.* (1996) put the Galactic RCB population resulting from the same scenario at about 300 stars, and calculated that the FF scenario would imply anywhere from 30 to 2,000 RCB stars at any given time. All of the evidence thus far suggests that there are many more than the ~65 known RCB stars in the Galaxy (see, for example, Zaniewski *et al.* 2005). The number of RCB stars expected in the Galaxy can be extrapolated from the LMC RCB population, using the method described by Alcock *et al.* (2001), and including all the new LMC stars. This implies a population of RCB stars in the Galaxy of almost 5,700. 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). On the other hand, FF stars, since they are single WDs, should typically have masses of 0.55–0.6 $M_{\odot}$ (Bergeron *et al.* 2007).

The merger rate of He+CO DDs is predicted to be ~ 0.018 yr^{-1} in the Galaxy (Han 1998). As of 1988, only one such DD system was actually known to exist (Saffer *et al.* 1988). The SPY project and other surveys have studied many WDs for evidence of binarity and the number of known DD systems is now ~100 (see, for example, Nelemans *et al.* 2005; Kilic *et al.* 2010, 2011; Parsons *et al.* 2011; Brown *et al.* 2011; Badenes and Maoz 2012). To see how well this number matches the predicted number of RCB stars in the Galaxy, we need to estimate how long an RCB star formed from a DD merger will live. This lifetime can be calculated as, $t = \Delta M \times X \times Q/L$, where L is the luminosity of RCB stars, ΔM is the accreted mass of He, X is the mass fraction of He in the accreted material, and Q is the energy generated when one gram of He is burned to ^{12}C. Assuming that $Q \sim 7 \times 10^{18}$ erg, $\Delta M = 0.1 M_{\odot}$, $X = 0.3$, and $L = 10{,}000\,L_{\odot}$, $t \sim 3 \times 10^{5}$ yr. Using the estimate of Han (1998) for the production of RCB stars from DD mergers, then the predicted population of RCB stars in the Galaxy at any given time would be ~5,400 which agrees well with the number extrapolated from the LMC above.

4. Evolutionary history

Table 3 summarizes the observational data that must be addressed by evolutionary models of RCB stars (Asplund *et al.* 2000, Jeffery *et al.* 2011). They are discussed below with respect to the FF and DD models. Two entries, the high abundance of silicon and sulphur, and the anti-correlation of hydrogen with iron, cannot be well explained by either scenario. The condensation of certain elements into dust has been suggested for the Si/S problem, although it is unclear that this would work (Asplund *et al.* 2000). The H/Fe anti-correlation is unexplained but Sakurai's Object follows the same trend.

4.1. Do RCB stars evolve from final flash stars?

The light curve behavior and spectroscopic appearance of V605 Aql in 1921 and more recently of Sakurai's Object are reminiscent of the RCB class. There are, however, several reasons why FF stars are unlikely to be the evolutionary precursors of the majority of RCB stars. The FF objects have deeper light declines (> 10 magnitudes) than do RCB stars (~ 8 magnitudes). This may be due to the fact that RCB stars have more dust lying near the star which scatters light around the intervening dust cloud. This may account for the flat-bottom appearance of deep RCB declines. See Figure 1. The abundances of FF objects, shortly after the outburst, do appear similar to those of RCB stars, except for some interesting differences. First there are significant amounts of ^{13}C present in Sakurai's Object, but not in most RCB stars. In the two years after it appeared, Sakurai's Object had $^{12}C/^{13}C \sim 4$ (Pollard *et al.* 1994; Asplund *et al.* 1999; Pavlenko *et al.* 2004). In general, RCB stars have $^{12}C/^{13}C \geq 100$. However, a few RCB stars do have detectable ^{13}C including both majority and minority stars. V CrA, V854 Cen, VZ Sgr, and UX Ant have measured $^{12}C/^{13}C < 25$ (Rao and Lambert 2008; Hema *et al.* 2012). Second, there is no sign of ^{18}O in the IR CO bands of Sakurai's Object (Eyres *et al.* 1998). Finally, several Galactic and LMC RCB stars, including R CrB, itself, show significant Lithium in their atmospheres (Rao and Lambert 1996; Asplund *et al.* 2000; Kipper and Klochkova 2006a). Renzini (1990) suggested that in a FF the ingestion of the H-rich envelope leads to Li-production through the Cameron-Fowler mechanism (Cameron and Fowler 1971). The abundance of Li in the atmosphere of the FF star, Sakurai's object, was actually observed to increase with time (Asplund *et al.* 1999).

In general, Sakurai's abundances resemble V854 Cen and the other minority-class RCB stars with 98% He and 1% C (Asplund *et al.* 1998). Although only low resolution spectra are available for V605 Aql from 1921, it likely had similar abundances (Clayton and De Marco 1997). New spectra obtained of V605 Aql in 2000 indicate that it has evolved from $T_{eff} \sim 5000$ K in 1921 to ~ 95,000 K today (Clayton *et al.* 2006). The new spectra also show that V605 Aql now has stellar abundances similar to those seen in [WC] central stars of PNe with ~55% He, and ~40% C. In the present state of evolution of V605 Aql, we may be seeing the not too distant future of Sakurai's Object. There are indications that Sakurai's Object is evolving along a similar path (Kerber *et al.* 2002; Hajduk *et al.* 2005). Some doubt has recently been thrown on the FF nature of V605 Aql on the grounds of high neon abundances found in its ejecta (Wesson *et al.* 2008; Lau *et al.* 2011).

For a very short time, perhaps as short as two years, both V605 Aql and Sakurai's Object were almost indistinguishable from the RCB stars. Unfortunately, this extremely short RCB phase of the FF stars means that they cannot account for even the small number of RCB stars known in the Galaxy.

4.2. Do RCB stars evolve from white dwarf mergers?

RCB and HdC stars have $^{16}O/^{18}O$ ratios close to and in some cases less than unity, values that are orders of magnitude lower than measured in any other stars (the Solar value is 500) (Clayton *et al.* 2005, 2007; García-Hernández *et al.* 2010). The three HdC stars, that have been measured, have $^{16}O/^{18}O < 1$, lower values than any of the RCB stars. These discoveries are important clues in determining the evolutionary pathways of HdC and RCB stars, whether the DD or the FF. No overproduction of ^{18}O is expected in the FF scenario. New hydrodynamic simulations indicate that WD mergers may very well be the progenitors of O^{18}-rich RCB and HdC stars (Longland *et al.* 2011; Staff *et al.* 2012).

Webink (1984) proposed that an RCB star evolves from the merger of a He-WD and a CO-WD which has passed through a common envelope phase. He suggested that as the binary begins to coalesce because of the loss of angular momentum by gravitational wave radiation, the (lower mass) He-WD is disrupted. A fraction of the helium is accreted onto the CO-WD and starts to burn, while the remainder forms an extended envelope around the CO-WD. This structure, a star with a helium-burning shell surrounded by a ~100 $R_\odot$ hydrogen-deficient envelope, closely resembles an RCB star (Clayton 1996; Clayton *et al.* 2007). The merging times (~10^9 yr) might not be as long as previously thought, which makes the DD scenario an appealing alternative to the FF scenario for the formation of RCB stars (Iben *et al.* 1996, 1997). In addition, Sai"EHo and Jeffery (2002) suggested that a WD-WD merger could also account for the elemental abundances seen in RCB stars. Pandey *et al.* (2006) have suggested a similar origin for the EHe stars.

The isotope, ^{18}O, can be overproduced in an environment of partial He-burning in which the temperature and the duration of nucleosynthesis are such that the $^{14}N(\alpha,\gamma)\,^{18}F(\beta^{+})\,^{18}O$ reaction chain can produce ^{18}O, if the ^{18}O is not further processed by $^{18}O(\alpha,\gamma)\,^{22}Ne$ (Warner 1967; Lambert 1986; Clayton *et al.* 2007). The surface compositions of HdC and RCB stars are extremely He-rich (mass fraction 0.98), indicating that the surface material has been processed through H-burning. After H-burning via the CNO cycle, ^{14}N is by far the most abundant of the CNO elements, because ^{14}N has the smallest nuclear p-capture cross-section of any stable CNO isotope involved. However, the majority of RCB stars have log *C/N* = 0.3 and log *N/O* = 0.4 by number, equivalent to mass ratios of *C/N* = 1.7 and *N/O* = 2.2 (Asplund *et al.* 2000). The N/O ratio represents the average for the majority RCB stars although the individual stars show a large scatter. Thus C is the most abundant and O the least abundant CNO element. These abundances are consistent if the material at the surfaces of HdC and RCB stars experienced a small amount of He-burning, as, for example, at the onset of a He-burning event that is quickly terminated. This partial He-burning would not significantly deplete He, but could be sufficient for some of the ^{14}N to be processed into ^{18}O. At the onset of He-burning, ^{13}C is the first α-capture reaction to be activated because of the large cross-section of $^{13}\mathrm{C}(\alpha, \mathrm{n})\,^{16}\mathrm{O}$. Thus, a large ^{12}C/^{13}C ratio and enhanced s-process elements are both consistent with partial He-burning.

As mentioned above, some RCB stars show enhanced Li abundances, as does the FF star Sakurai's Object (Lambert 1986; Asplund *et al.* 1998). As shown by Herwig and Langer (2001), Li enhancements are consistent with the FF scenario. However, the production of ^{18}O requires temperatures large enough to at least marginally activate the $^{14}\mathrm{N}(\alpha, \gamma)$ reaction. The α capture on Li is eight orders of magnitude more effective than on ^{14}N. For that reason, the simultaneous enrichment of Li and ^{18}O is not expected in the WD merger scenario. This is an important argument against the FF evolution scenario as a progenitor of RCB and HdC stars with excess of ^{18}O. The abundance of ^{18}O cannot be directly measured in R CrB because it is too hot to have CO, but it is overabundant in ^{19}F, which does imply a high ^{18}O abundance (Pandey *et al.* 2008). Since ^{18}O strongly supports the DD merger/accretion scenario, the obvious solution is that there could be (at least) two evolutionary channels leading to RCB, HdC and EHe stars, perhaps with the DD being the dominant mechanism. Unfortunately the division between majority- and minority-class RCB stars does not lend itself naturally to this explanation, since Li has only been detected in the majority group (Asplund *et al.* 2000).

4.3. Mass-Loss and dust formation

It has long been accepted that the characteristic RCB declines in brightness are caused by the formation of optically thick clouds of carbon dust (Loreta 1935; O'Keefe 1939; Clayton 1996). But the formation mechanism is not well understood. Empirical analysis of the spectroscopic and light curve evolution during declines implies that the dust forms close to the stellar atmosphere and then is accelerated to hundreds of km s^{-1} by radiation pressure (Clayton *et al.* 1992; Whitney *et al.* 1993). There is strong evidence for variable, high-velocity winds in RCB stars associated with dust formation (Clayton *et al.* 2003, 2012). The HdC stars, which produce no dust, also have no evidence for winds (Geballe *et al.* 2009). Other observational evidence indicates that there is also gas moving much more slowly away from the star (see, for example, García-Hernández *et al.* 2011a and references therein).

The observed timescales for RCB dust formation fit in well with those calculated by carbon chemistry models which show that the dust forms near the surface of the RCB star due to density and temperature perturbations caused by stellar pulsations (Feast 1986; Woitke *et al.* 1996). There is a strong correlation between the onset of dust formation and the pulsation phase in several RCB stars (Crause *et al.* 2007). All RCB stars show regular or semiregular pulsation periods in the 40- to 100-day range (Lawson *et al.* 1990). The dust forming around an RCB star does not form in a complete shell, but rather in small "puffs" (Clayton 1996). Only when a puff forms along the line of sight to the star will there be a decline in brightness. Studies of UV extinction and IR re-emission of stellar radiation indicate that the covering factor of the clouds around RCB stars during declines is $f<0.5$ (Feast *et al.* 1997; Clayton *et al.* 1999b; Hecht *et al.* 1984, 1998). The typical dust mass of a puff is $\sim 10^{-8}\,M_{\odot}$ (Feast 1986; Clayton *et al.* 1992).

In the recent deep decline of R CrB, shown in Figure 1, the puff dust mass is $\sim 10^{-8}\,M_{\odot}$, assuming the dust forms at $2\,R_*$ ($R_* = 85\,R_{\odot}$), and that a puff subtends a fractional solid angle of 0.05 (Clayton *et al.* 2011a). Since the dust would accelerate and dissipate quickly due to radiation pressure, dust must be formed continually by R CrB to maintain itself in a deep decline for four years or more. If a puff forms during each pulsation period (~40 days), R CrB would be producing $\sim 10^{-7}\,M_{\odot}$ of dust per year. Assuming a gas-to-dust ratio of 100 (Whittet 2003), the total mass loss rate is $10^{-5}\,M_{\odot}\,yr^{-1}$.

Little is known about the lifetime of an RCB star. We have a lower limit from the fact that R CrB itself has been an RCB star for 200 yr (Pigott and Englefield 1797). The large diffuse dust shell around R CrB, seen in the far-IR, could possibly be a fossil PN shell (Clayton *et al.* 2011a). Assuming an expansion velocity of a PN shell (~20 km s^{-1}), then the shell would take 10^5 yr to form. If the mass-loss was more like the high-velocity winds seen in RCB stars today (~200 km s^{-1}), then the shell would be about an order of magnitude younger (Clayton *et al.* 2003). If R CrB is the result of a FF rather than a DD, then the size and timescales would be consistent with the nebulosity, now seen in far-IR emission, being a fossil PN shell. The nebulosity, including cometary knots, seen around R CrB and UW Cen looks very much like a PN shell (Clayton *et al.* 1999b, 2011a). The mass of the shell is estimated to be $\sim 2\,M_{\odot}$, which is consistent with it being a PN (Clayton *et al.* 2011a). Adaptive optics and interferometry have been used to study dust very close to RCB stars (de Laverny and Mékarnia 2004; Bright *et al.* 2011, and references therein).

Any gas lost during a DD event would have far less mass. If the shell is an old PN shell then this would suggest that R CrB is the product of an FF event rather than a DD merger. R CrB is one of the stars with lithium on its surface, also a possible indicator of an FF. About 10% of single stars will undergo a final-flash event (Iben *et al.* 1996). About this percentage of RCB stars (R CrB, RY Sgr, V CrA, and UW Cen) show evidence of resolved fossil dust shells (Walker 1994).

Understanding the RCB and HdC stars is a key test for any theory that aims to explain hydrogen deficiency in post-AGB stars. Solving the mystery of how the RCB stars evolve is an exciting possibility, but it will also be a watershed event in the study of stellar evolution that could lead to a better understanding of other types of stellar merger events such as type Ia supernovae.

The observations in the AAVSO database have been invaluable to my research on RCB stars throughout my career. For R CrB alone, there are a staggering 238,136 brightness estimates in the AAVSO International Database, stretching back to 1843. The usefulness of the AAVSO data is only increasing with the addition of digital data which allow the low-amplitude RCB star pulsations to be studied in detail. The AAVSO International Database is a model for the many other photometric databases coming on line. The need for longterm monitoring combined with reliable photometry is essential for the identification and characterization of the many transient objects that are being discovered.

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Table 1. Spectroscopically confirmed Milky Way RCB stars.

Name	R.A. (2000)			Dec. (2000)			Max	Spec. Ref.[1]	^{18}O	F	Li	Notes[2]
	h	m	s	°	′	″						
XX Cam	04	08	38.75	+53	21	39.5	8.7	1		x	x	—
SU Tau	05	49	03.73	+19	04	22.0	9.5	1		✓	✓	—
UX Ant	10	57	09.06	–37	23	55.0	12.2	1		x	x	^{13}C
UW Cen	12	43	17.18	–54	31	40.7	9.6	1	x	✓	✓	—
Y Mus	13	05	48.19	–65	30	46.7	10.5	1	x		x	—
DY Cen	13	25	34.08	–54	14	43.1	12.0	1				hot RCB
V854 Cen	14	34	49.41	–39	33	19.2	7.0	1	x	x	x	Minority, ^{13}C
Z UMi	15	02	01.33	+83	03	48.6	11.0	1	x		✓	Minority
S Aps	15	09	24.53	–72	03	45.1	9.6	1	✓			—
ASAS-RCB-1	15	44	25.08	–50	45	01.2	11.9	2				V409 Nor
R CrB	15	48	34.41	+28	09	24.3	5.8	1		✓	✓	—
ASAS-RCB-9	16	22	28.83	–48	35	55.8	11.3	2, 3				IO Nor
RT Nor	16	24	18.68	–59	20	38.6	11.3	1			x	—
RZ Nor	16	32	41.66	–53	15	33.2	11.1	1			✓	
ASAS-RCB-2	16	41	24.75	–51	47	43.4	12.0	2				—
ASAS-RCB-3	16	54	43.60	–49	25	45.0	11.8	2, 3				—
ASAS-RCB-12	17	01	01.41	–50	15	34.8	11.8	2				—
ASAS-RCB-4	17	05	41.25	–26	50	03.4	13.3	2, 3				GV Oph
V517 Oph	17	15	19.74	–29	05	37.6	12.6	1				—
ASAS-RCB-10	17	17	10.21	–20	43	15.7	11.5	2				—
EROS2-CG-RCB-12	17	19	58.50	–30	04	21.3	14.1	4				—

Table continued on following pages

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
V2552 Oph	17	23	14.55	–22	52	06.3	10.8	5, 6		✓	x	—
EROS2-CG-RCB-7	17	29	37.09	–30	39	36.7	14.1	4				—
EROS2-CG-RCB-6	17	30	23.83	–30	08	28.3	12.8	4				V1135 Sco
V532 Oph	17	32	42.61	–21	51	40.8	11.7	7				—
OGLE–GC–RCB–1	17	35	18.12	–26	53	49.2	14.6	8				—
EROS2-CG-RCB-8	17	39	20.72	–27	57	22.4	13.0	4				—
EROS2-CG-RCB-10	17	45	31.41	–23	32	24.4	12.5	4				—
EROS2-CG-RCB-5	17	46	00.32	–33	47	56.6	13.5	4				—
EROS2-CG-RCB-4	17	46	16.20	–32	57	40.9	12.5	4				—
EROS2-CG-RCB-9	17	48	30.87	–24	22	56.5	15.2	4				—
EROS2-CG-RCB-11	17	48	41.53	–23	00	26.5	12.3	4				—
ASAS-RCB-7	17	49	15.70	–39	13	16.0	12.7	2				V653 Sco
EROS2-CG-RCB-1	17	52	19.96	–29	03	30.8	12.4	4				—
ASAS-RCB-5	17	52	25.30	–34	11	28.0	12.3	2				—
EROS2-CG-RCB-2	17	52	48.70	–28	45	18.9	14.5	4				—
MACHO 401.48170.2237	17	57	59.02	–28	18	13.1	14.5	9				—
EROS2-CG-RCB-3	17	58	28.27	–30	51	16.4	11.1	4				—
EROS2-CG-RCB-13	18	01	58.22	–27	36	48.3	11.4	4				—
V1783 Sgr	18	04	49.74	–32	43	13.4	12.5	2				—
WX CrA	18	08	50.48	–37	19	43.2	11.0	1	✓			—
ASAS-RCB-11	18	12	03.30	–28	08	33.0	12.0	2				—

Table continued on following pages

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
V739 Sgr	18	13	10.54	–30	16	14.7	14.0	1				—
EROS2-CG-RCB-14	18	13	14.86	–27	49	40.9	12.5	4				—
V3795 Sgr	18	13	23.58	–25	46	40.8	11.5	1		✓		Minority
VZ Sgr	18	15	08.58	–29	42	29.4	11.8	1		✓	x	Minority, ^{13}C
IRAS 18135–2419	18	16	39.20	–24	18	33.4	12.8	2, 10				—
RS Tel	18	18	51.22	–46	32	53.4	9.3	1			x	—
MACHO 308.38099.66	18	19	27.36	–21	24	08.2	16.3	9				—
MACHO 135.27132.51	18	19	33.87	–28	35	57.8	14.3	9				—
GU Sgr	18	24	15.58	–24	15	26.5	11.3	1		✓?	x	—
V581 CrA	18	24	43.46	–45	24	43.8	10.0	2				—
V391 Sct	18	28	06.57	–15	54	44.7	13.3	2				—
MACHO 301.45783.9	18	32	18.60	–13	10	48.9	17.3	9				—
NSV 11154	18	37	51.26	+47	23	23.5	12.0	11				—
V348 Sgr	18	40	19.93	–22	54	29.3	10.6	1				hot RCB
MV Sgr	18	44	31.97	–20	57	12.8	12.0	1				hot RCB
FH Sct	18	45	14.84	–09	25	36.1	13.4	1		✓?	x	—
V CrA	18	47	32.30	–38	09	32.3	9.4	1		✓?	x	^{13}C
ASAS-RCB-8	19	06	39.87	–16	23	59.2	10.9	2				—
SV Sge	19	08	11.76	+17	37	41.2	11.5	1	✓			—
V1157 Sgr	19	10	11.83	–20	29	42.1	12.5	1				—
RY Sgr	19	16	32.76	–33	31	20.4	6.5	1		✓	x	—

Table continued on next page

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)* *h*	*m*	*s*	*Dec. (2000)* *°*	*′*	*″*	*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*[2]
ES Aql	19	32	21.61	–00	11	31.0	11.6	12	✓			—
V482 Cyg	19	59	42.57	+33	59	27.9	12.1	1		✓?	x	—
ASAS-RCB-6	20	30	04.96	–62	07	59.2	13.1	2, 3				AN 141.1932
U Aqr	22	03	19.70	–16	37	35.2	10.5	1	✓		✓?	—
UV Cas	23	02	14.62	+59	36	36.6	11.8	1		✓	x	—
HdC Stars												
HE 1015–2050	10	17	34.232	–21	05	13.87	16.0	13				—
HD 137613	15	27	48.316	–25	10	10.15	7.5	14	✓			—
HD 148839	16	35	45.788	–67	07	36.69	8.3	14	x		✓	—
HD 173409	18	46	26.627	–31	20	32.07	9.5	14	x			—
HD 175893	18	58	47.29	–29	30	18.08	9.4	14	✓			IR Excess
HD 182040	19	23	10.08	–10	42	11.54	7.0	14	✓			—

[1] *Spectroscopic references: 1) Clayton (1996, and references therein), 2) Tisserand et al. (2012, in preparation), 3) Miller et al. (2012), 4) Tisserand et al. (2008), 5) Hesselbach et al. (2003), 6) Rao and Lambert (2003), 7) Clayton et al. (2009), 8) Tisserand et al. (2011), 9) Zaniewski et al. (2005), 10) Greaves (2007), 11) Kijbunchoo et al. (2011), 12) Clayton et al. (2002), 13) Goswami et al. (2010), 14) Warner (1967), .*

[2] *Note: RZ Nor has a faint blue star nearby. This may explain why the RZ Nor declines are not very deep and it appears bluer during declines.*

Table 2. Spectroscopically confirmed LMC and SMC RCB stars.

Name	R.A. (2000)			Dec. (2000)			Max	Spec. Ref.[1]	^{18}O	F	Li	Notes
	h	m	s	°	′	″						
LMC Stars												
EROS2-LMC-RCB-3	04	59	35.78	–68	24	44.68	14.3	1				—
HV 12524	05	01	00.36	–69	03	43.2	14.5	2				MACHO 18.3325.148
KDM 2373	05	10	28.50	–69	47	04.3	13.8	1, 3				MACHO 5.4887.14, EROS2-LMC-RCB-2
HV 5637	05	11	31.37	–67	55	50.6	15.8	4				MACHO 20.5036.12
EROS2-LMC-RCB-1	05	14	40.17	–69	58	40.1	15.2	1				MACHO 5.5489.623
HV 2379	05	14	46.20	–67	55	47.4	14.9	2				MACHO 16.5641.22
MACHO 79.5743.15	05	15	51.79	–69	10	08.6	15.2	2				—
MACHO 6.6575.13	05	20	48.21	–70	12	12.5	15.3	2				—
HV 942	05	21	48.00	–70	09	57.4	15.0	2				MACHO 6.6696.60
MACHO 80.6956.207	05	22	57.37	–68	58	18.9	16.0	2				—
W Men	05	26	24.52	–71	11	11.8	13.8	4			✓	MACHO 21.7407.7
MACHO 80.7559.28	05	26	33.91	–69	07	33.4	15.8	2				—
MACHO 81.8394.1358	05	32	13.36	–69	55	57.8	16.3	5				—
HV 2671	05	33	48.94	–70	13	23.4	16.1	5				MACHO 11.8632.2507, Hot RCB
EROS2-LMC-RCB-4	05	39	36.97	–71	55	46.4	15.1	1				MACHO 27.9574.93
KDM 5651	05	41	23.49	–70	58	01.8	14.4	3				MACHO 15.9830.5
HV 12842	05	45	02.88	–64	24	22.7	13.7	4			✓	—

Table continued on next page

Table 2. Spectroscopically confirmed LMC and SMC RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	*^{18}O*	*F*	*Li*	*Notes*
	h	*m*	*s*	°	′	″						
MACHO 12.10803.56	05	46	47.74	–70	38	13.5	15.1	2				—
KDM 7101	06	04	05.53	–72	51	23.1	14.2	1, 3				EROS2-LMC-RCB-5
SMC Stars												
RAW 21	00	37	47.40	–73	39	02.0	15.6	1, 3, 6				EROS2-SMC-RCB-1
RAW 476	00	48	22.87	–73	41	04.7	15.5	1, 6				EROS2-SMC-RCB-2
EROS2-SMC-RCB-3	00	57	18.12	–72	42	35.3	16.0	1, 6				MACHO 207.16426.1662

[1] *Spectroscopic references: 1) Tisserand et al. (2009), 2) Alcock et al. (2001), 3) Morgan et al. (2003), 4) Clayton (1996, and references therein), 5) Alcock et al. (1996), 6) Tisserand et al. (2004).*

Table 3. DD vs FF[1]

Property	*DD*	*FF*
Extreme H deficiency but some H present	yes?	yes
H abundance anti-correlated with Fe	?	?
Li abundance high in 5 stars (all majority)	no	yes
C/He ~ 1%	yes	no
^{12}C/^{13}C > 500	yes	no
High N, O	yes	yes
High Na, Al	yes?	yes
High Si, S	?	?
Enrichment of s-process elements	yes?	yes
Abundance uniformity/non-uniformity for majority/minority	no?/yes	yes/no?
Similar to Sakurai's object	no	yes
Nebulosity present in a few stars	yes?	yes
RCB Lifetime	yes	no
Lack of binarity	yes	no?
^{18}O and ^{19}F greatly enhanced in (all?) stars	yes	no
M_V = –3 to –5 mag	yes	yes
Mass = 0.8–0.9 $M_\odot$	yes	no?

[1] *Adapted and updated from Table 7 of Asplund et al. (2000).*

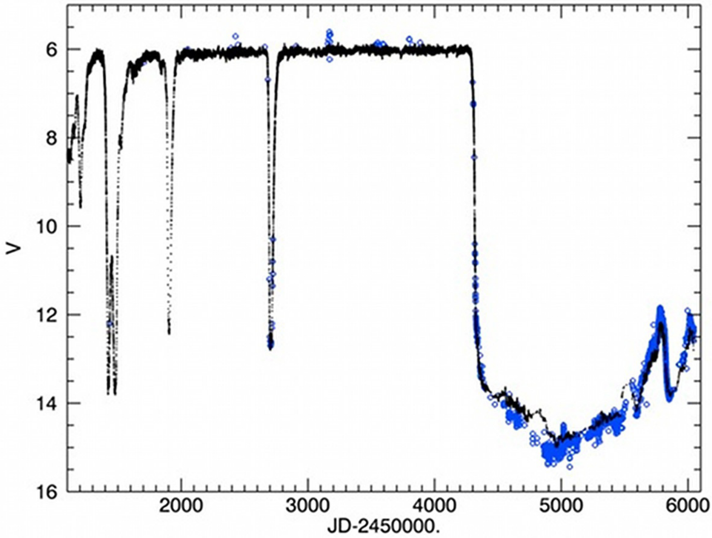

Figure 1. Light curve of R CrB from 1998 to 2012 using AAVSO data. Visual magnitudes are plotted as black dots. Johnson V data are plotted as open circles.

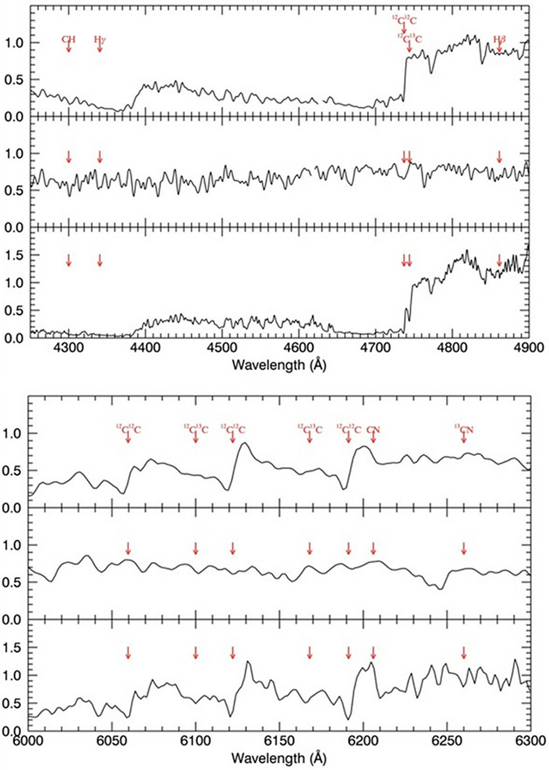

Figure 2. Blue (upper figure) and red (lower figure) sections of the spectra of a cool RCB star, S Aps (top plots), and a warm RCB star, RY Sgr (middle plots), as well as the carbon star, RV Sct (bottom plots), showing some of the spectroscopic features that define RCB stars.

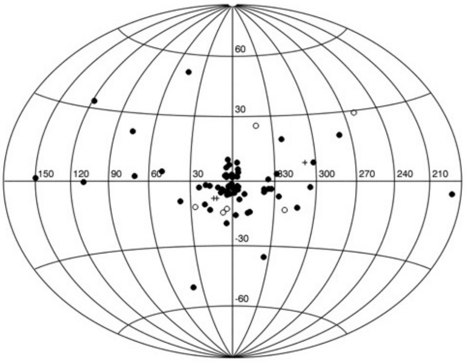

Figure 3. Distribution of RCB stars on the sky in the Galaxy showing that they are consistent with an old, bulge popularion. Cool RCB stars (filled circles), hot RCB stars (crosses), HdC stars (open circles).