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The R Coronae Borealis Stars – A Few Mere Facts

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Abstract. This review presents a selection of recent highlights of observations of R Coronae Borealis variables. Emphasis is placed on an abundance analysis of a complete sample (18 stars) of the warm galactic RCBs. It is shown that 14 of the 18 have very similar compositions: the iron mass fraction ranges about a factor of 3 around the solar value (assuming C/He = 3%) but abundance ratios X/Fe for elements from Na to Ba show little variation. By contrast, the other 4 stars are deficient in iron but not in Na, Si, S and some other elements. With for example, [Si/Fe] $\simeq 2$, the quartet is indeed 'peculiar'. One of the quartet, V854 Cen shows depletions of elements (other than CNO) similar to the depletions seen in interstellar medium corresponding to average $\log n(H_{\text{tot}}) = -1.5$. Scenarios for creating RCB from normal single and double stars are summarised.

Key words: Hydrogen deficient stars—irregular variables—abundances—evolution.

1. Introduction

This modest essay attempts to introduce a fascinating class of rare variable stars – the R Coronae Borealis (RCB) stars – and to provide a few highlights from our continuing collaboration into their structure, composition, and origins. The collaboration grew out of the Mysore meeting in 1985 on 'Hydrogen Deficient Stars and Related Objects'. There, our review (Lambert 1986) of the chemical compositions of RCBs concluded with Samuel Taylor Coleridge's exclamation: "how mean a thing a mere fact is except as seen in the light of some comprehensive truth". The English essayist and poet's remark taken from an essay 'A Prefatory Observation on Modern Biography' was uncovered just prior to the Mysore meeting. Our pursuit of RCB stars is, of course, aimed at establishing the 'comprehensive truth', namely placing the stars correctly in the context of stellar evolution. But in 1985 the lack of 'mere facts' – the abundances of the chemical elements – could be seen as limiting the search for the comprehensive truth. This limitation led us to begin a collaboration on a thorough spectroscopic examination of the RCBs beginning with determinations of the chemical compositions

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of the warmer members of the class, i.e., the stars with the more tractable spectra. Here, we summarize the progress in the context of a general discussion of the class.

R Coronae Borealis stars, as a class, are defined by two main characteristics:

- First, the spectrum of a RCB star suggests that the atmosphere is hydrogen deficient: the Balmer lines are weaker than expected for a supergiant and may even be absent. The lines of C I are strong and for the cooler stars the C_2 Swan bands are prominent in the visual spectrum. The combination of H-deficiency and C-enrichment has suggested that the atmospheres consist primarily of material exposed to He burning.
- Second, the variability portrayed by the class is unique. At irregular intervals the stars decline rapidly by up to 5–8 magnitudes and may remain faint for extended periods. The dimming is attributed to obscuration of the star by a cloud of carbon dust grains.

2. Some basic data

Before discussing the chemical compositions of the RCB stars, we shall summarize the stars' known properties. Emphasis is placed on the more recent findings. The chemical compositions are discussed later.

Catalogue: Drilling & Hill (1986) provide a list of 20 'cool' and 3 'hot' RCBs. One star (LR Sco) listed by Drilling & Hill is not a RCB (Giridhar, Rao & Lambert 1991). To the 1986 list of 'cool' RCBs should be added: UX Ant (Herbig 1990; Kilkenny & Westerhuys 1990), V854 Cen (McNaught & Dawes 1986), and V739 Sgr, V1159 Sgr, V1783 Sgr (Lloyd Evans, Kilkenny & van Wyk 1991), V1860 Sgr, V4017 Sgr (Herbig 1990), V517 Oph (Kilkenny *et al.* 1992) and FH Sct. At present, then there are 32 known galactic RCBs.

Spectrum at maximum light: The stars span a range in effective temperature from about 20000 K (DY Cen, early B-type, and V348 Sgr, WC11-like) to cool carbon stars resembling the R stars (WX CrA and S Aps with $T_{\rm eff} = 4000$ K). A majority of the RCBs spectroscopically resemble the F–G Ib supergiants with $T_{\rm eff} = 7000 \pm 1000$ K. Of course, the Balmer lines and the CH bands are weaker and the CI lines and C_2 bands are stronger in the RCBs than in normal supergiants. It could be noted that the H deficiency may not always take extreme values. In particular, the recently discovered RCB V854 Cen shows Balmer lines with pronounced Stark broadened wings indicative of a substantial H abundance.

Absolute luminosities: Estimates of luminosity are difficult to obtain for the galactic RCBs. Most probably, the best estimates are provided from the three RCBs identified in the Large Magellanic cloud: $M_V = -4$ to -5 (Feast 1979). Estimates for galactic RCBs are generally consistent with this range (e.g. Rao & Lambert 1993a).

Galactic distribution and kinematics: Drilling (1986) reviewed the galactic distribution and kinematics. The RCBs are concentrated towards the galactic center. The distribution of radial velocities (referred to the local standard of rest) shows that the majority of the RCBs follow the galactic rotation curve appropriate to a galactocentric distance of about 4 kpc. About 5 or 6 of the RCBs are high velocity objects. Several are to be found at quite large distances (about 2 kpc) from the galactic plane.

Light variations – Irregular declines: As noted above, these declines which may reach 5–8 magnitudes are a defining characteristic of the class. RCB stars, in general, spend most of their time at or near maximum brightness and suddenly undergo declines with an initial phase lasting a few days to a few weeks. The decline to minimum may not be smooth: 'halts' are sometimes reported. Minima generally last several weeks to months with some variations in brightness. Recovery to maximum brightness often takes much longer than the decline. The frequency of declines varies from star to star. XX Cam has apparently experienced but one shallow decline in the last 100 years (Rao, Ashok & Kulkarni 1980). By contrast, V854 Cen, the third brightest RCB at maximum light, is more often found in decline than at maximum light which presumably explains why this RCB was not recognised until 1986. In those cases where observations are extensive, statistical analysis shows that declines occur at random intervals (Sterne 1935; Howarth 1976, 1977).

Light Variations – Pulsations: In addition to the dramatic declines, RCBs show minor variations in visual light of 0.1 to 0.5 mag. in amplitude and with pseudoperiods averaging about 40 days (Feast 1990; Lawson *et al.* 1990). Only in the case of RY Sgr these variations may be said to be regular and due to atmospheric pulsations. RY Sgr's period of 38.6 days is not constant but according to Kilkenny (1982) and Marraco & Milesi (1982) decreases at the rate of 0.15 day/cycle – see also Lawson & Cottrell (1990). There is evidence that declines of RCBs occur at maximum light in the pulsational cycle (Lawson *et al.* 1992) but quite obviously many maxima may pass before a decline is initiated or, in the words of Lawson *et al.* "it is possible to predict when a decline *might* happen, although not when it will *occur*".

Infrared excesses: Circumstellar dust is betrayed by infrared excesses in the near-infrared ($< 12\,\mu$m). In several cases and notably for the eponymous star RCrB infrared excesses are detected at wavelengths as long as $100\,\mu$m. For reviews of the infrared excesses and the circumstellar dust see Feast (1986) and Walker (1986). A representation of the near-infrared fluxes by a blackbody results in dust temperatures of 600–900 K. The infrared flux from RY Sgr has been shown to vary at the photospheric pulsation period showing that the dust is heated by photospheric radiation (Feast *et al.* 1977; Feast 1986). In a decline, however, the infrared flux remains approximately unchanged despite the several magnitudes dimming in visible light. If the decline is caused by the onset of dust formation above the visible photosphere, the dust resident in the shell prior to the decline must subtend a solid angle at the star greater than that initially subtended by the new cloud. In addition to the warm (700 K) dust, much cooler and more extended dust shells have been detected around RCrB and SU Tau (Rao & Nandy 1986; Gillett *et al.* 1986; Walker 1986). RCrB's cool shell which extends 18′ on the sky corresponding to a linear size of about 8 pc has been interpreted as a hydrogen rich shell ejected earlier.

Polarimetric observations. A few stars have been observed for polarization at visual wavelengths near maximum light. Observations of linear polarization for RCrB suggest that the dust formation and ejection occurs in a preferred plane (Stanford *et al.* 1988). A similar preference has been suggested for V854 Cen (Rao & Raveendran 1993). Few observations of polarization have been reported for stars near minimum light. One key observation by Whitney *et al.* (1992) of V854 Cen in a deep minimum showed the emission lines (see below) were unpolarized but the continuum was quite strongly polarized; hence, the emission lines come from regions not obscured by dust.

Nebulae around RCB stars: Several RCBs are associated with low density low excitation nebulae. RCrB's nebula was revealed by Herbig's (1949, 1968) detection of the [O II] 3727 Å lines at minimum light. Spectra of the hotter RCBs – DY Cen, MV Sgr, V348 Sgr – show nebular forbidden emission lines (Rao, Giridhar & Lambert 1993; Rao, Houziaux & Giridhar 1990; Pandey, Rao & Lambert 1993; Herbig 1958). Extended nebulosity of 30″ diameter has been detected around V348 Sgr by Pollacco, Tadhunter & Hill (1990). A reflection nebulosity around UW Cen was reported by Pollacco *et al.* (1991). Broad emission lines of [N II], [O I] and [S II] in the spectrum of V854 Cen in a deep minimum were reported by Rao & Lambert (1993b) and interpreted as coming from a bipolar nebula with an orthogonal thick dusty accretion disk. V605 Aql which at maximum light in 1919 seems to have had the spectrum of a cool RCB (Bidelman 1973) is now a faint stellar object ($V = 22.3$) surrounded by the planetary nebula A58 which has helium enriched knots (Pollacco *et al.* 1992) and so resembles the planetary nebulae A30 and A78 (Hazard *et al.* 1980; Jacoby & Ford 1983). FG Sge, the most enigmatic of peculiar supergiants, has long been known to be associated with a planetary nebula. In its recent RCB-like decline, FG Sge showed strong C_2 bands and has been advanced for membership in the RCB class (Kipper & Kipper 1993; Jurcsik 1993).

Spectrum at minimum light: The spectrum in the decline to minimum light has been well documented for RCrB (Payne-Gaposchkin 1963; Cottrell, Lawson & Buchhorn 1990), and RY Sgr (Alexander *et al.* 1972). The reader is referred to these papers for descriptions of the 'chromospheric' emission lines which are generally sharp and blue-shifted by about $10\,\mathrm{km\,s^{-1}}$ relative to the photosphere. The photospheric lines remain visible during the decline with an enhancement of low excitation lines such as the C_2 Swan bands (Lambert, Rao & Giridhar 1990). Very few spectra have been reported for stars in deep minima; the reader may surmise the logistical reasons for this lacuna in our knowledge of RCBs. Rao & Lambert (1993b) discuss a high resolution spectrum of V854 Cen showing sharp 'chromospheric' lines and broad emission lines (FWHM $= 200$–$300\,\mathrm{km\,s^{-1}}$) of Ca II H and K, Na D, Hα the C_2 Swan bands as well as the forbidden lines listed above. Old reports speak of the absorption lines as 'veiled' (i.e., present but weakened) in spectra of RCrB at minimum but in V854 Cen the continuum was unaccompanied by absorption lines and even the very strongest photospheric lines were absent. A set of unidentified broad emission lines may be linked to the carriers of interstellar diffuse bands (Rao & Lambert 1993c).

Evolutionary sequence?: Putative relatives of the RCBs are recognizable on both the low and high temperature boundaries of the RCB domain from about 20000 K to 4000 K. The hydrogen deficient carbon (HdC) stars are likely relatives with effective temperatures ranging up to the low temperature boundary of the RCBs. This linkage was first drawn by Bidelman (1953) who noted that four non-variable stars were "apparently hydrogen-deficient stars which appear also to be rich in carbon". The prototype is HD182040. Five galactic examples are now known. The classic (and only) abundance analysis is by Warner (1967); we comment below on whether the results of Warner's analysis of the HdC and our new analysis of the RCBs would encourage promotion of an evolutionary link. At the high effective temperature limit for RCBs, the extreme helium stars are probable relatives; the similarities in composition between the RCBs and EHes is noted later. The HdC, RCB and EHe stars form a sequence of approximately constant luminosity running in the ($\log g$, $\log T_{\mathrm{eff}}$) plane from about (0.5, 3.8) to (3.0, 4.5). We do not include spectroscopic binaries like υ Sgr in our definition of an EHe.

The existence of this sequence suggests but does not demand an evolutionary connection between the three classes. Additional information is needed to discern the direction of an evolutionary sequence. A further question is suggested by the rarity of these hydrogen deficient stars: Do few single or binary stars become RCBs or is the RCB phase a very short-lived event in the life of many single or double stars?

In an attempt to answer these questions we began our study of the chemical compositions of RCBs with an initial emphasis on the warmer stars – 18 in all – whose spectra are dominated by atomic lines rather the forbidding rich spectra of the C_2 and CN molecules. In the following section we sketch the preliminary results of our analysis.

3. Chemical compositions

Our 1986 review of the chemical compositions of RCBs drew upon detailed analyses of three stars (RCrB, XX Cam, RY Sgr) and less complete and curve of growth analyses of 3 additional stars (U Aqr, UV Cas, SU Tau). Presently, we have results for 18 stars including 5 of the above 6 with U Aqr considered too cool for present consideration. The hot RCB DY Cen was analysed recently by Jeffery & Heber (1993). We also analysed 2 EHes which with 4 discussed in Heber's (1986) review provide a useful sample for comparison with the RCBs. Knowledge of the HdCs' compositions is restricted to that provided by Warner (1967).

Spectra for our analysis were gathered primarily at the Cerro Tololo Inter-American Observatory with the Cassegrain echelle at the 4 m telescope. The spectral resolution is 0.2 to 0.3 Å. The wavelength coverage is 5000–7000 Å. The S/N ratio is generally 100 or better. Similar spectra were obtained at the McDonald Observatory for several northern RCBs. Sample spectra are shown in Figs. 1 and 2.

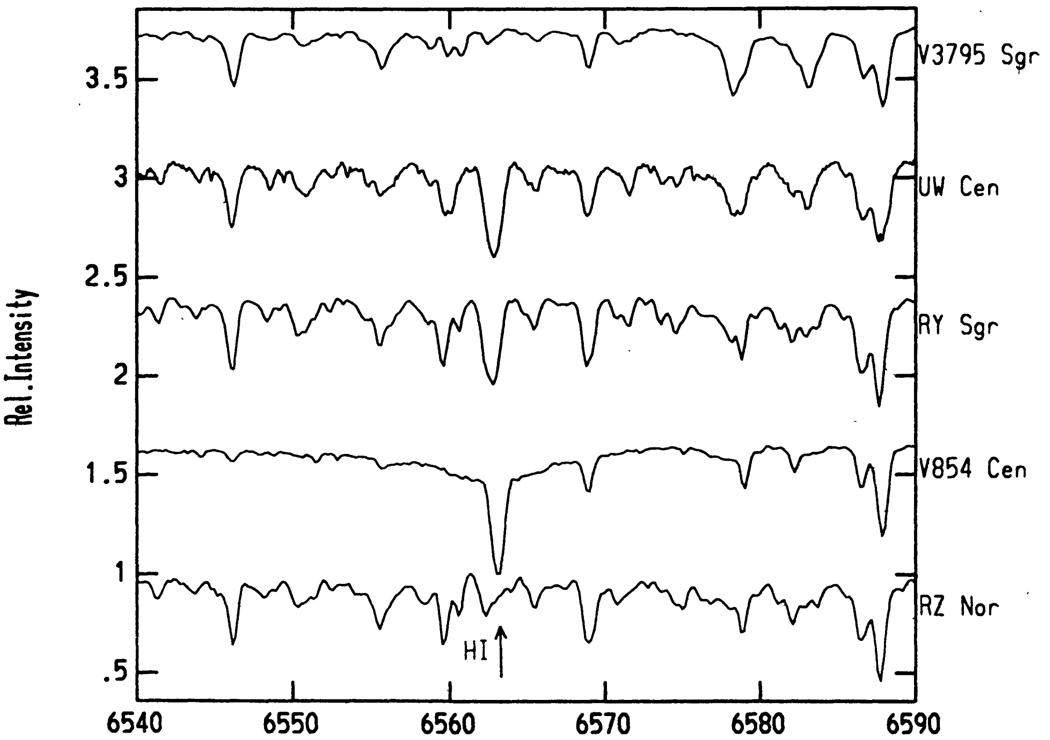

Figure 1. Spectra of V3795 Sgr, UW Cen, RY Sgr, RZ Nor, and V854 Cen near the Hα line at 6563 Å. Note the broad wings of Hα for V854 Cen and the absence of Hα from V3795 Sgr.

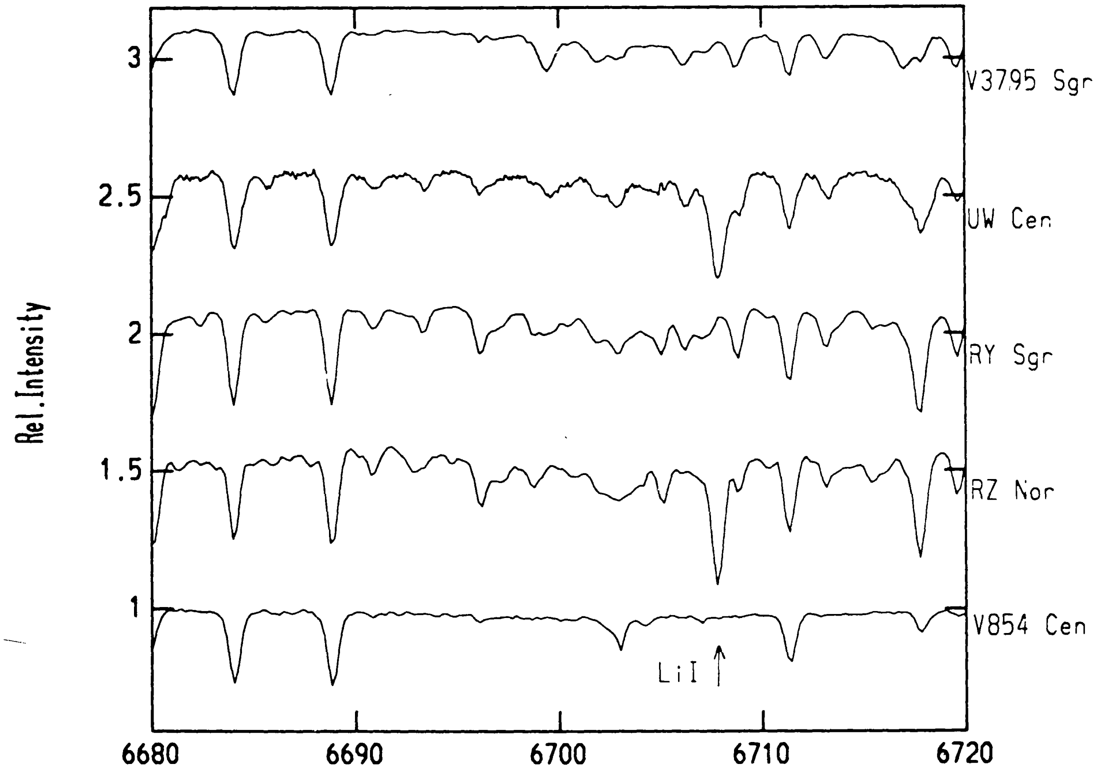

Figure 2. Spectra of V3795 Sgr, UW Cen, RY Sgr, RZ Nor, and V854 Cen near the Li I resonance doublet at 6707 Å. The Li I doublet is present in RZ Nor and UW Cen but absent from the other three spectra.

For the analysis of the spectra, we have used a family of model atmospheres kindly provided by D. Schönberner – see Schönberner (1975). We are grateful to U. Heber for supplying models of hotter stars. Model atmospheres were available for C/He ratios of 1 and 3% by number at a H abundance too low for H to contribute to the continuous opacity and with a solar mix of elements other than H, He and C. A computer program originally written by Sneden (1973) was adapted to meet the special requirements of RCB atmospheres by adding several sources of continuous opacity. The model atmospheres and the analysis assumes local thermodynamic equilibrium.

In discussing the compositions of the RCBs it is essential to define clearly what is meant by 'the abundance of an element'. Abundance of an element *E*, as determined by spectroscopic analysis, is commonly taken to identify the number density ratio $n(E)/n(\mathrm{H})$ which we may write as E/H. This is a natural definition because the continuous opacity in normal stellar atmospheres in spectral regions usually used for abundance analyses is controlled by hydrogen atoms or the negative H ions. For the RCB atmospheres, however, carbon atoms probably control the continuous opacity unless either the C/He ratio is extremely small or the H/C is quite large. If carbon dominates the continuous opacity, the equivalent width of a C I line in a RCB spectrum is expected to be almost independent of the C/He ratio. Furthermore, the equivalent width is expected to be insensitive to the atmosphere's effective temperature and gravity because the continuous opacity which arises from photoionization of neutral carbon atoms is contributed by C I energy levels of only slightly higher excitation energies than the levels providing the observed C I lines. Our spectra show that the equivalent width of a given C I line is almost unchanged across the sample of stars despite their obvious differences in effective temperature, gravity and H content. This is evidence that carbon (or an element correlated with carbon) dominates the continuous opacity. It is not evidence that carbon is the most abundant element; helium is the most abundant element (Schönberner 1975).

On the assumption that carbon dominates the continuous opacity, the 'spectroscopic' abundance is $S(E) = E/\mathrm{C}$. The more fundamental quantity is $Z(E)$, the mass fraction of the element E, where

$$Z(E) = \frac{\mu_E}{\mu_\mathrm{C}} Z(\mathrm{C}) S(E) \tag{1}$$

and

$$Z(\mathrm{C}) = \frac{3\mathrm{C/He}}{(1 + 3\mathrm{C/He} + \ldots)} \tag{2}$$

and μ_E is the atomic mass of element E. Since $\mathrm{C/He} \ll 1$ we find from (1) and (2) that

$$Z(E) \simeq 3 \frac{\mu_E}{\mu_\mathrm{C}} \frac{\mathrm{C}}{\mathrm{He}} S(E) \tag{3}$$

Interpretation of the abundances is based in large part on the ratios of abundances but fortunately $Z(E_1)/Z(E_2) = S(E_1)/S(E_2)$ so that the possibly unknown factor C/He cancels.

The He I 5876 Å triplet is present in spectra of RCBs (Keenan & Greenstein 1963), but it is not an accurate indicator of the C/He ratio. Abundances given here are based largely on the model atmosphere grid computed for C/He = 3%. For the EHes and the hot RCB DY Cen, Heber and colleagues are able to derive the C/He ratio from helium and carbon lines (Heber 1986; Jeffery & Heber 1993): the mean ratio from 5 stars including DY Cen is C/He = 0.83% with a range of just 1.0 to 0.66% (Jeffery *et al.* (1988) derived a remarkably low C/He (= 0.02%) ratio for the hot RCB MV Sgr.) We comment as appropriate on the effect on our abundances of a change from 3 to 1% in the adopted C/He ratio.

Our abundance analysis included whenever possible the following elements: H, Li, C, N, O, Na, Al, Si, S, Ca, Fe, Ni, Y, and Ba. Additional elements were measured in some of the 18 RCBs (e.g., Ne, P, Zr, and Nd). A summary of the results appears in Table 1. Perhaps, the most significant finding is that the majority of the RCBs have an essentially common composition. Fourteen of the 18 RCBs comprise this majority. They are UX Ant, XX Cam, UV Cas, UW Cen, R CrB, V482 Cyg, Y Mus, RT Nor, RZ Nor, FH Sct, RY Sgr, GU Sgr, SU Tau, and RS Tel. We discuss next the composition of this majority.

Our analysis uses the model atmosphere grid constructed for a carbon to helium ratio of 3% and the abundances are normalized to $\log \Sigma N_i \varepsilon_i = 12.15$, i.e., $\log \varepsilon(\mathrm{He}) = 11.51$ and $\log \varepsilon(\mathrm{C}) = 10.0$. Analysis of a selection of C I lines returns a mean carbon abundance of $\log \varepsilon(\mathrm{C}) = 9.8 \pm 0.2$, which is slightly less than the adopted abundance but this difference could be erased in several acceptable ways; e.g., adopt an alternative choice of the source for the C I *f*-values. Unless otherwise stated all abundance are quoted for analyses based on C/He = 3% and normalized as above.

Table 1. Chemical compositions of R Coronae Borealis stars.

	log ε					
Elements	Sun[a]	Majority	Minority			
			V854 Cen	VCrA	VZSgr	V3795 Sgr
H	12.00	...[b]	11.2	9.8	7.2	<4.3
Li	3.31	...[b]	<1.9	<1.3	<2.3	<3.1
C	8.55	9.8 ± 0.2	9.7	9.6	9.7	9.2
N	7.97	9.7 ± 0.3	8.4	10.0	8.7	8.3
O	8.87	9.1 ± 0.5	9.2	9.9	9.5	8.0
Na	6.32	7.1 ± 0.3	6.5	6.6	6.8	6.2
Al	6.48	6.9 ± 0.2	5.5	6.0	6.4	6.3
Si	7.55	8.0 ± 0.3	7.3	8.7	8.3	8.0
S	7.23	7.8 ± 0.4	6.7	8.2	7.9	7.9
Ca	6.34	6.2 ± 0.2	5.2	6.4	6.0	5.3
Fe	7.51	7.5 ± 0.3	6.3	6.2	6.9	6.0
Ni	6.25	6.8 ± 0.4	6.0	6.2	6.3	6.3
Y	2.24	2.7 ± 0.6	2.3	1.2	3.7	2.0
Ba	2.21	1.9 ± 0.5	1.1	0.4	2.1	0.0

[a] Meteoritic/Solar abundances from Grevesse & Noels (1993) for C, N, O and Fe, and Anders & Grevesse (1989) for other elements. Based on He/H = 0.1 from Grevesse & Noels (1993) and, hence, $\log(\Sigma \mu_i \varepsilon_i) = 12.15$.

[b] See text.

The iron abundances (metallicity) of the majority span the range $\log \varepsilon(\text{Fe}) = 6.9$ (UX Ant) to $\log \varepsilon(\text{Fe}) = 8.0$ (XX Cam, UV Cas). The mean Fe abundance is the solar abundance. With our choice of C/He = 3% the most metal rich stars correspond to $[\text{Fe/H}] \simeq +0.5$ which might appear unusually high except that many of the RCBs are located towards the galactic centre where metallicities may be higher on average than in the solar vicinity. Recall from Equation 3 that mass fraction of iron depends on the assumed C/He ratio. If C/He = 1%, as analyses of the EHes and the hot RCB DY Cen (see above) suggest, the mass fractions of Fe are reduced by about 0.5 dex. Then the most Fe-rich RCBs have about the solar metallicity and the most metal-poor of this majority correspond to a metallicity of $[\text{Fe/H}] \simeq -1$. The assumption of C/He = 1% does seem to be preferable. Without a direct estimate of the C/He ratio for individual RCBs we cannot determine how to apportion the evident spread in the apparent metallicities between a real spread in the C/He ratio and a spread in the iron mass fractions. Our measurement errors should not exceed ± 0.2 to ± 0.3 dex.

A defining characteristic of the majority is the similarity of their elemental abundances, especially the abundance ratios with respect to Fe. Hydrogen and lithium are exceptions in this regard. The hydrogen abundances range from a maximum of $\log \varepsilon\,(\text{H}) = 8.3$ (SU Tau) to a minimum of $\log \varepsilon\,(\text{H}) < 4.9$ (XX Cam). The mean value of $\log \varepsilon\,(\text{H}) = 7.1 \pm 0.8$ (including the upper limit for XX Cam) corresponds to a hydrogen deficiency of 10^5. Four stars show a strong Li *T* 6707 Å resonance doublet. Lithium was first detected in RCBs by Keenan & Greenstein (1963) from spectra of the eponymous star. The Li-rich quartet are UW Cen, R CrB, RZ Nor, and SU Tau with a mean Li abundance of $\log \varepsilon\,(\text{Li}) = 4.3 \pm 0.3$. (The abundance is $\log \varepsilon\,(\text{Li}) \simeq 3.8$ for C/He = 1%.) Lithium appears overabundant with respect to the stars' initial Li abundance; the local abundance is now $\log \varepsilon$ (Li) = 3.3. Scenarios purporting to describe the origin of RCBs must, therefore, account for lithium production in some RCBs. The Li-rich stars seem to be a subclass of the majority because the upper limits on Li in the other 10 stars range from $\log \varepsilon$ (Li) < 2.6 to $\log \varepsilon$ (Li) < 1.6 in the coolest stars. The subclass have similar H abundances. (This abundance of Li is similar to that seen in super Li-rich luminous AGB stars in LMC (Smith & Lambert 1989, 1990) – could these Li rich RCBs be the luminous counterparts of the RCB population).

Inspection of Table 1 shows that nitrogen is greatly overabundant in this LTE analysis. The N abundance exceeds that attainable by the complete conversion of initial (solar) C, N, and O to N by the H-burning CNO-cycles; if C/He = 1% is assumed, the N abundance ($\log \varepsilon$ (N) = 9.2) is close to the upper limit provided by solar C, N, and O. The RCBs apparently contain material in which carbon synthesised in He-burning was partially converted to nitrogen on exposure to warm protons. This conclusion is reinforced by the observation that oxygen has a normal abundance in RCBs.

Sodium is overabundant: [Na/Fe] $\simeq$ + 1. Aluminium is slightly overabundant but calcium with a sensitivity to the model atmospheres similar to that of Na and Al has a normal abundance. One surmises that Na and Al have been synthesised prior to the formation of the RCBs. Synthesis of Na and Al necessarily accompanies the burning of H by the ON-cycles.

Mass fractions of silicon and sulphur exceed solar values by about 0.4 and 0.6 dex respectively. Although these excesses would vanish if we adopted C/He = 1%, the abundances relative to Fe would remain about 0.5 dex larger than the solar ratios. The Si and S abundances are not necessarily indicative of production of these elements. It is a well known feature of chemical compositions of stars that Si and S (relative to Fe) increase in abundance in metal-poor stars. Edvardsson *et al.* (1993) also show that the increase is more pronounced for stars originating from the inner regions of the Galaxy. We suppose that the Si and S enrichments may reflect an enrichment present at the birth of the RCBs. A difficulty with this claim is that Ca is seen to follow Si and S in normal stars but not in the RCBs.

There is a suggestion in our analyses that there is a real spread in the Y and Ba abundances across the sample of 14 RCBs. On average, yttrium is overabundant by about 0.5 dex but barium has a normal or slightly sub-normal abundance.

Four of the 18 RCBs have compositions that set them apart from the majority. The four are V854 Cen, V CrA, VZ Sgr, and V3795 Sgr. Put in the simplest way possible, the quartet are distinguished by having a low metallicity (Fe) but 'normal' abundances of Si (and some other elements): $\log \varepsilon$ (Fe) = 6.0 to 6.9 and $\log \varepsilon$ (Si) = 7.3 to 8.7 for the quartet but $\log \varepsilon$ (Fe) = 6.9 to 8.0 and $\log \varepsilon$ (Si) = 7.4 to 8.4 for the majority of 14. We comment on the elemental abundances from H to Ba in the quartet relative to the abundances of the majority. Abundances are given in Table 1.

Hydrogen: A myth that *all* RCBs are extremely deficient in hydrogen is exploded by our analyses. Significantly, the two most hydrogen-rich RCBs are members of the minority quartet: V854 Cen (see Fig. 1) and V CrA with H deficiencies of a factor of 10 and a factor of 100 respectively. The quartet also includes the most H-poor RCB of the entire sample of 18: V3795 Sgr with a deficiency of at least a factor of 18^8.

Nitrogen and oxygen: The abundances of N and O for the sample of 18 RCBs are compared in Fig. 3. A 'low' N abundance is found for 3 of the quartet of 'unusual'

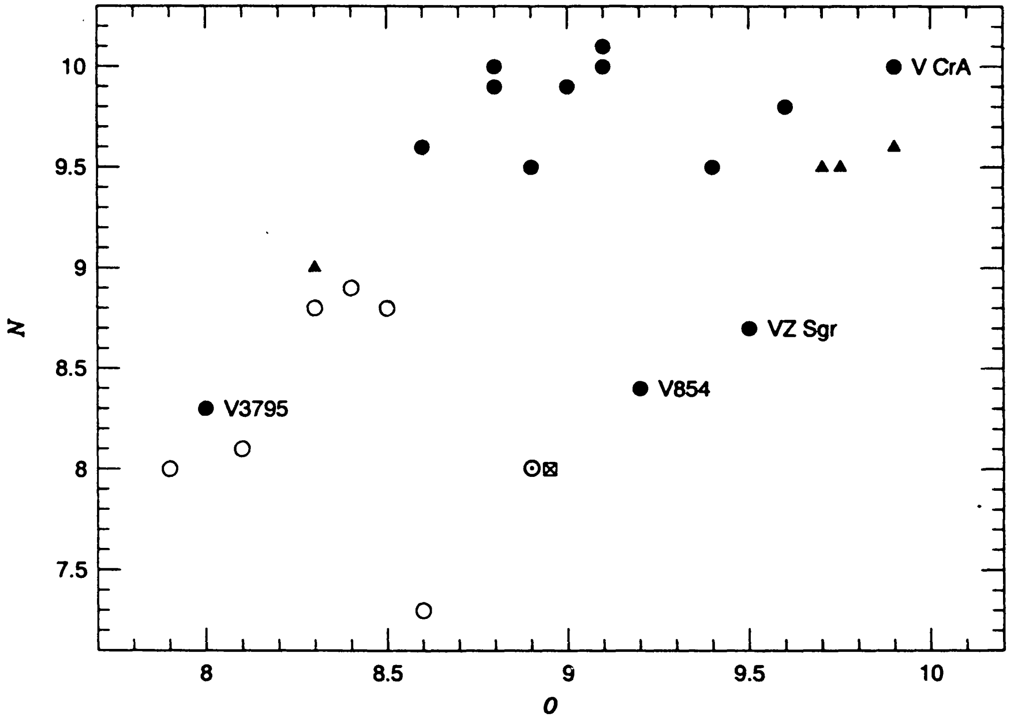

Figure 3. Nitrogen and oxygen abundances of the RCB and EHe stars. The 18 RCBs of our samples are represented by the filled symbols with the Li-rich stars by filled triangles. EHes are represented by open circles and the hot RCB DY Cen by the cross. The solar composition is denoted by the usual symbol. The points representing the peculiar RCBs are labelled. Location of solar N and O abundance is marked by the usual symbol.

RCBs but V CrA is one of the most N-rich and O-rich of all the RCBs. In Fig. 3, there appears to be a separation between the RCBs and the EHes and the hot RCB DY Cen. In part, this is a result of our assumption that C/He = 3%. If C/He = 1%, as analyses of the EHes and DY Cen indicate, the N and O abundances would be reduced by about 0.5 dex but this revision would not bring the mean N and O abundances of the RCBs to the level of the EHes.

Sodium through Calcium: The quartet is distinguished by the fact that Na, Al, Si, and S are not, as is Fe, underabundant (except V854 Cen). In other words, the stars display remarkably high abundance ratios of these elements relative to Fe. Fig. 4 illustrates this point. Calcium is overabundant relative to Fe in 2 of the 4 stars. (Note too the small scatter in ratios such as Si/Fe and Na/Fe among the majority sample of 14 RCBs.) Si and S are well correlated – see Fig. 5.

Iron and Nickel: A distinctive feature of the quartet is that the Ni/Fe ratio is much larger than for the majority and distinctly non-solar.

Yttrium and Barium: Figs. 6 and 7 show Y and Ba as a function of the Fe abundances for the sample of 18 RCBs and the members of the quartet are individually labelled. With the exception of VZ Sgr, the entire sample is distributed with a marked scatter about a line of constant Y/Fe ratio which is offset from the solar ratio by about 0.8 dex. The barium abundances (Fig. 7) show that the Ba/Fe ratio is approximately constant and solar for the RCBs with VZ Sgr having a Ba/Fe ratio only slightly above the average for RCBs. The scatter in Y/Fe at a given Fe abundance exceeds that in Ba/Fe and for both ratios the scatter exceeds that readily attributed to errors

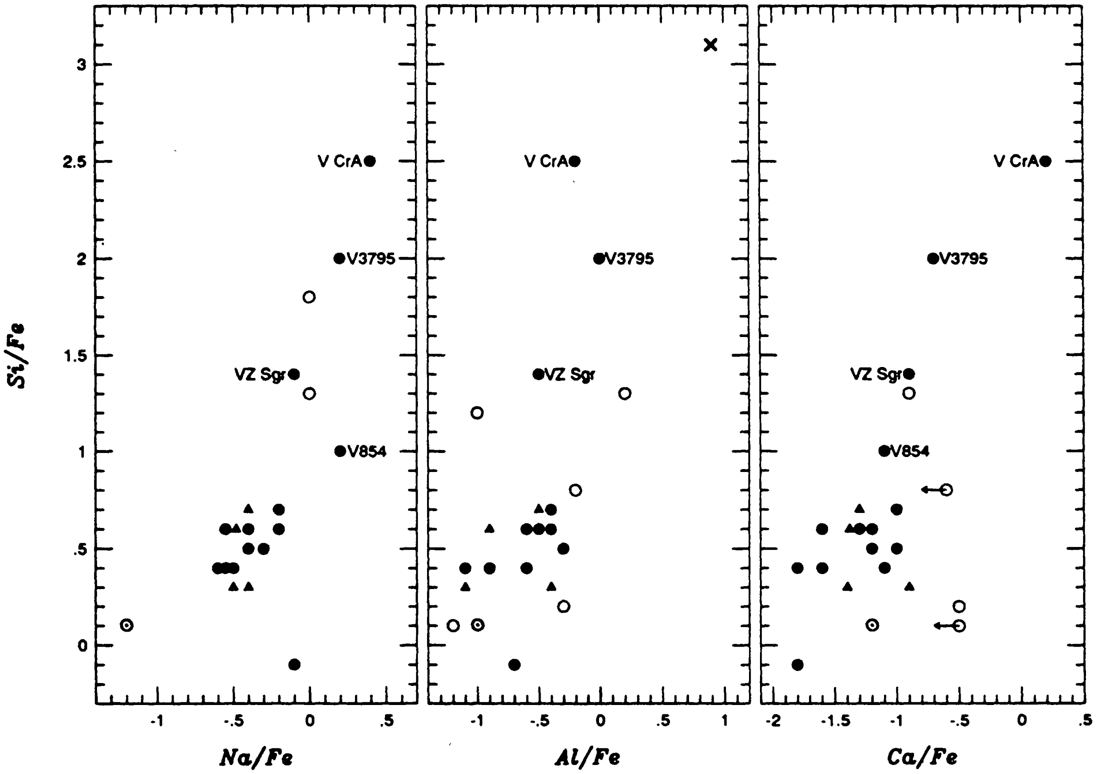

Figure 4. The ratio Si/Fe vs. Na/Fe, Al/Fe, and Ca/Fe. See the caption to Fig. 3 for the key to the symbols.

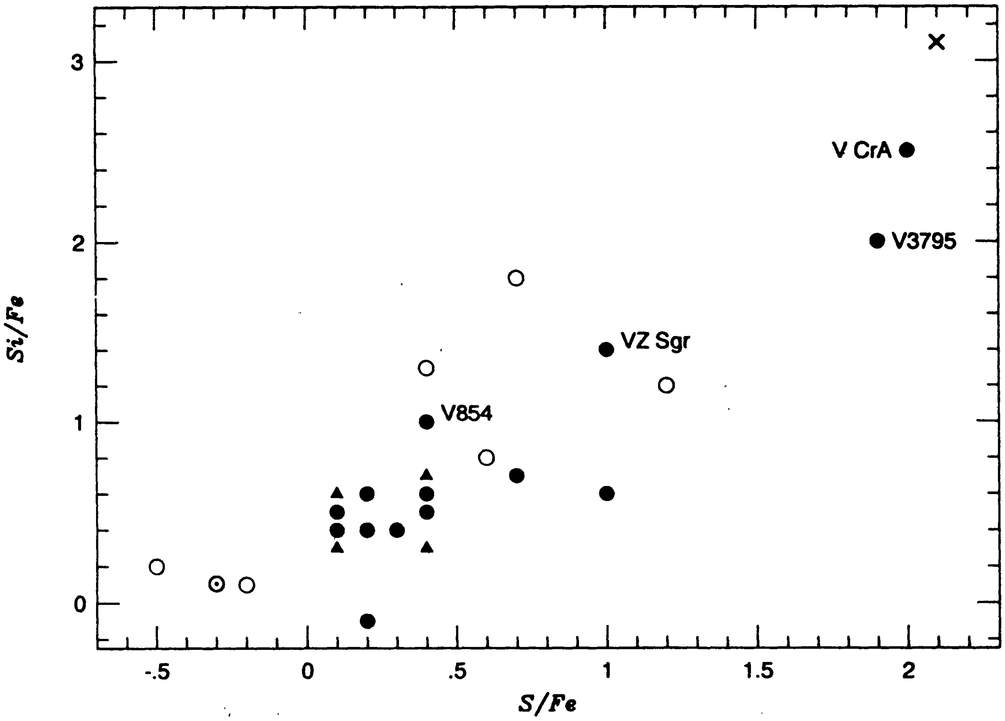

Figure 5. The ratio Si/Fe vs. S/Fe. See the caption of Fig. 3 for the key to the symbols.

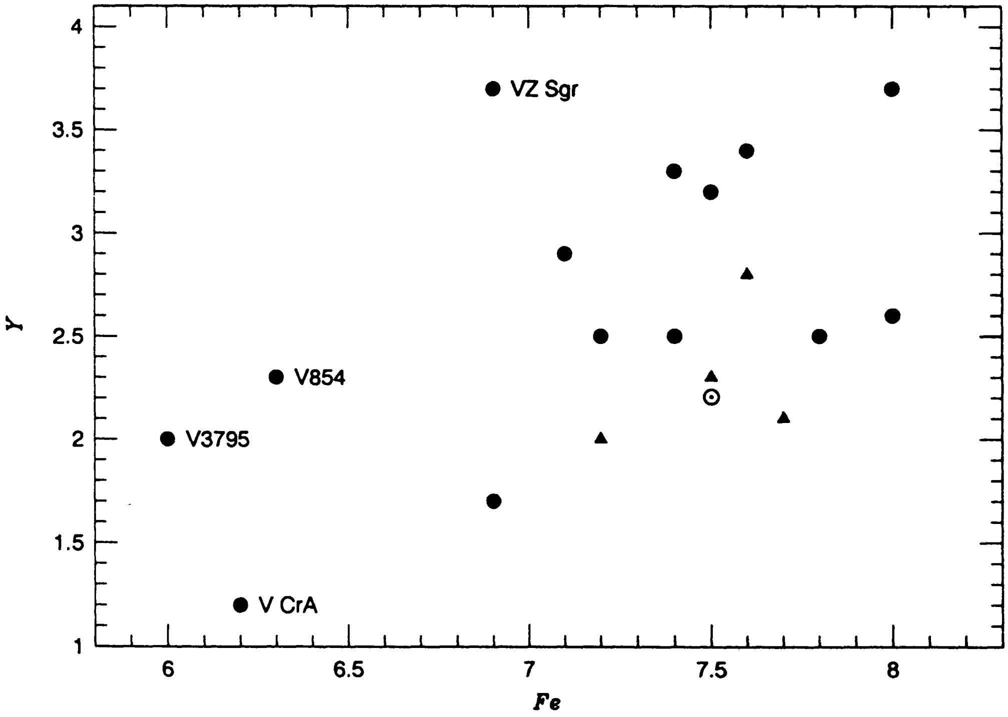

Figure 6. Yttrium and iron abundances of the RCB and EHe stars. See the caption to Fig. 3 for the key to the symbols.

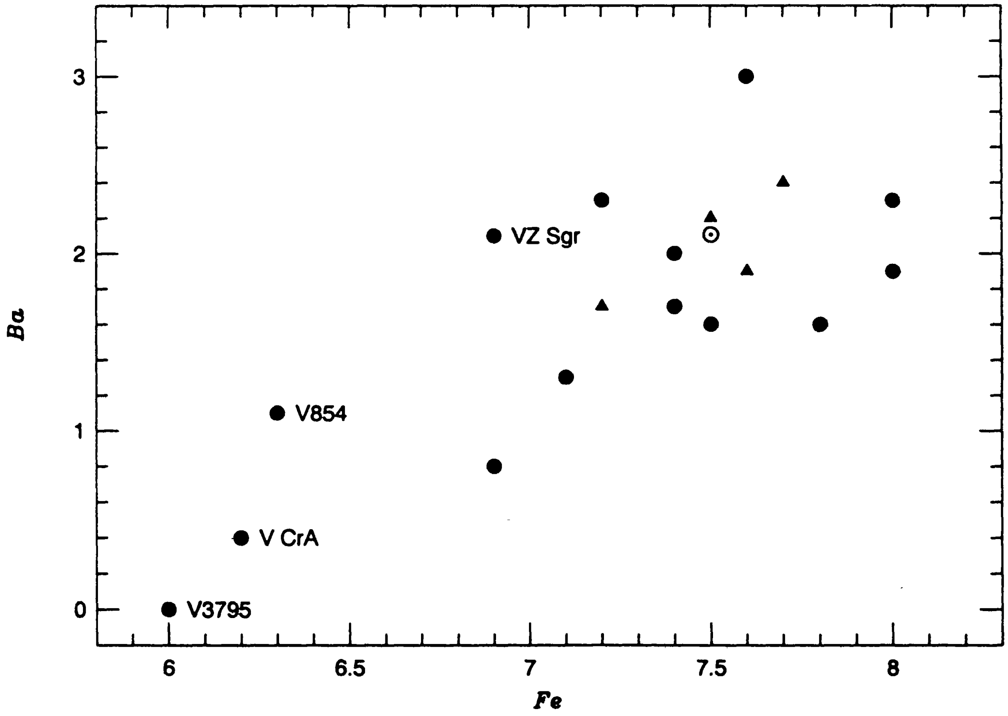

Figure 7. Barium and iron abundances of the RCB and EHe stars. See the caption to Fig. 3 for the key to the symbols.

of measurement. There is a hint that the Y/Ba ratio, which also shows a large scatter, declines with increasing metallicity. Unless a systematic error vitiates the analyses, the result that the Y/Ba is higher than the solar ratio implies that *s*-processing products in RCBs have been more mildly exposed to the *s*-process than material comprising the solar system.

As putative relatives of the RCBs, it is of interest to note how the compositions of the EHes and the hot RCB DY Cen relate to those of the RCBs. Where available, the abundances of the EHes and DY Cen have been shown in Figs. 3 through 7. It is apparent that the EHes and DY Cen span the same range in compositions as the RCBs – see, for example, Fig. 5. One striking fact is that none of the 6 EHes appear to have the composition of the majority sample of 14 RCBs. DY Cen, the hot RCB, is the most metal-poor of the combined sample of EHes and RCBs with log ε (Fe) = 5.0 but with abundances of Ne, Mg, Al, Si, P, S, and Ar that are near or above the solar abundances: e.g., [Fe/H] = -2.5 but [X/H] = $+1.5$ (Ne), $+0.6$ (Si), and -0.1 (S). DY Cen may be regarded as an extreme member of the peculiar minority of RCBs.

4. Composition and origins of RCBs

4.1 *Boundary Conditions*

At the beginning of our endeavours, we supposed that a comprehensive abundance analysis ('mere facts') would surely lead to novel and thorough insights into the evolutionary history of RCBs ('the comprehensive truth'). A reading of this section will show that we are far from recognising the comprehensive truth but, perhaps, other minds will discern this truth among our enlarged collection of mere facts.

Prerequisites to our jottings on the origins of the RCBs should be the succinct discussions by Schönberner (1986) and Renzini (1990). Schönberner establishes that He giants such as the RCB and HdCs may be either low mass stars ($0.7 \lesssim M/M_\odot \lesssim 2$) burning He in a shell around a C–O electron degenerate core or more massive stars ($2 \lesssim M/M_\odot \lesssim 2.7$) burning C in the core or a shell. The latter identification is most probably not a satisfactory one for a majority of RCBs because it implies that the original star was quite massive, a requirement in conflict with the galactic distribution and kinematics of the RCBs. We suppose that most of the RCBs are low mass He/C–O stars.

It is not known whether these low mass stars were created as He main sequence stars or as He-rich supergiants. The former evolve on exhaustion of He in their cores into He-rich supergiants. The supergiants, if the electron-degenerate core has a mass less than $1.4M_\odot$, evolve through a phase as an EHe to the top of the white dwarf cooling track. It is as yet impossible to decide observationally whether the RCBs were formed as supergiants or evolved from EHes – see Schönberner (1986). He-rich supergiants with a core mass exceeding the Chandrasekhar mass will explode as a supernova.

Scenarios for the formation of RCBs and EHes must meet two conditions set by observations (Schönberner 1986; Renzini 1990):

- The progenitors must belong to a rather old galactic population, i.e., if the progenitor is a single star, it must be of low mass or if the progenitor is a double star, a slow process of production is required;

- The conversion of the progenitor to a H-deficient star must provide an envelope that
  (α) – retains (or accretes) a small amount of the envelope(s) of the original star(s);
  (β) – contains material exposed heavily to the H-burning CN-cycle and possibly the ON-cycles;
  (γ) – contains substantial amounts of material exposed to He-burning.

These three conditions (α, β, γ) are based on the results of the abundance analyses conducted prior to our survey. Condition (α) recognizes that H is present in trace amounts in most RCB (and EHes). Condition (β) is imposed because the N abundance is high; N is produced during H-burning, but converted to Ne during He-burning. Condition (γ) is needed to account for the relatively high observed abundance of ^{12}C. Amplification and extension of these conditions is now suggested by our survey. First, Li production must be possible in a proposed evolutionary scenario. Second, a scenario must be devised to account for Fe-poor RCBs and EHes with near-normal abundances of other lighter elements (e.g. Ne, Al, Si, S) commonly lumped with Fe as 'metals': the Si/Fe and S/Fe ratios recorded for the extreme RCBs (i.e., $[\mathrm{Si/Fe}] \simeq [\mathrm{S/Fe}] \simeq 2$) have no precedents among H-rich stars of low (or high) metallicity.

4.2 *Is Iron a Metallicity Indicator?*

Metallicity of a star is most commonly identified with the iron abundance which is taken to be Fe/H for a normal star. In the case of the RCBs, it has usually been assumed that the mass fraction of iron is unaltered as normal stars are transformed to RCBs. In the light of the very peculiar elemental abundances of some RCBs and EHes, it seems timely to question whether the low Fe abundances of some stars are indeed the initial Fe abundances of these stars.

Three simple possibilities deserve consideration:

(i) the low Fe abundances result from an underestimate of the C/He ratio;
(ii) the atmospheric compositions have been altered by a diffusive or chemical separation (fractionation) of elements;
(iii) the atmospheric compositions are primarily the result of the changes wrought by nucleosynthesis.

Hypothesis (i) is surely untenable for two reasons. First, the low Fe abundance of several EHes and the hot RCB DY Cen cannot be attributed to the assumed low C/He ratio because in these cases the C/He ratio is measured explicitly from C II, C III, and He I lines. Second, although the C/He ratio adopted for our analyses of the RCBs could be raised to increase the inferred Fe abundance (see Equation 3), ratios such as Si/Fe would remain highly anomalous and require explanation. Moreover, a very high C/He ratio would be demanded.

Under the umbrella of possibilities represented by (ii), the current favourite is a separation of dust and gas such that present photospheres consist of gas from which condensable elements have been removed in the form of dust grains. This hypothesis was invoked by Venn & Lambert (1990) to explain the unusual compositions of λ Bootis stars (young main sequence stars of type A) and post-AGB stars. (As we discuss below the RCBs are quite possibly a variety of post-AGB stars.) In their discussion of DY Cen, Jeffery & Heber (1993) allude to removal of iron in the form of dust grains. Unfortunately, the pattern of the elemental abundances is not easily reconciled with that of gas from which dust has removed condensable elements (except in V854 Cen – see below). Certainly, the RCBs are factories for dust grains but one imagines carbon grains and silicon carbide to be the dominant material along with MgS (Sedlmayr 1989 – however the 11.3 μm feature attributed to SiC is not present in any RCB spectrum obtained so far). If this is correct and there is exchange of material between the atmosphere and the site of dust formation, silicon will be removed from the atmosphere as the grains are driven out by radiation pressure. But the 'peculiar' RCBs (except V854 Cen) are Si-rich and Fe-poor! If the site of dust-gas separation is made the oxygen-rich atmosphere of an earlier evolutionary stage of the RCB (say, the immediate post-AGB phase), one expects the abundances to reflect the pattern of depletions of elements in interstellar gas (Jenkins 1987, 1989) and in very metal-poor post-AGB stars (Bond 1991).

The abundance pattern indicated by one of the stars of the metal poor quartet, V854 Cen does show this aspect of fractionation. The differential abundances with respect to sun (depletions) are shown in Fig. 8 along with the average depletions seen in interstellar medium for hydrogen density of $\log n(H_{\text{tot}}) = -1.5$ (Jenkins 1987). Except for CNO elements, the match of V854 Cen depletions to the ISM depletions is surprisingly good. Sulphur is relatively more depleted (may be locked up in MgS) and Ni is less depleted in V854 Cen than in ISM. Thus there is a strong possibility that the Fe poorness in V854 Cen is due to the grain depletion as seen in some post-AGB stars. However there is little similarity in the remaining three stars of the quartet for such a pattern: for example, the post-AGB stars have a low Si/S ratio and Si and Fe are rather similarly depleted.

By elimination, hypothesis (iii) (or an as-yet-unidentified alternative) stands. The most outstanding puzzle in explaining the anomalous abundances of the peculiar RCBs and EHes in terms of nucleosynthesis does not, of course, concern C, N, and O, which may be attributed to H and He burning, but the unusual ratios such as Si/Fe, S/Fe and Ni/Fe. In this regard, we conceive of two extreme possibilities:

- the measured Fe abundance is or is quite similar to the initial abundance but the abundances of Si and other elements have been increased by nucleosynthesis;
- the measured abundances of Si and other elements are approximate indicators of the star's initial composition and the Fe abundance has been drastically lowered by nucleosynthesis.

In principle, iron may be transmuted into heavier elements by neutrons, as in the *s*-process. This seems unlikely to be applicable here because the Y and Ba abundances of the peculiar RCBs are approximately the values initially expected for a star of low Fe abundance not the much higher values expected if Si not Fe is a measure of the initial metallicity. Very severe exposures to neutrons would convert iron-group nuclei to nuclei (Tl, Pb, Bi) at the termination of the *s*-process path. Exceptionally mild exposures would process the iron-group nuclei to slightly heavier nuclei (Cu–Br). Since we have as yet not measured the abundances of either these nuclei just above the iron-group or the very heavy nuclei, we cannot definitively eliminate these extreme exposures. But the fact that the Y/Si and Ba/Si ratios are distinctly non-solar would seem to exclude the possibility that a mild exposure has reduced the Fe abundance.

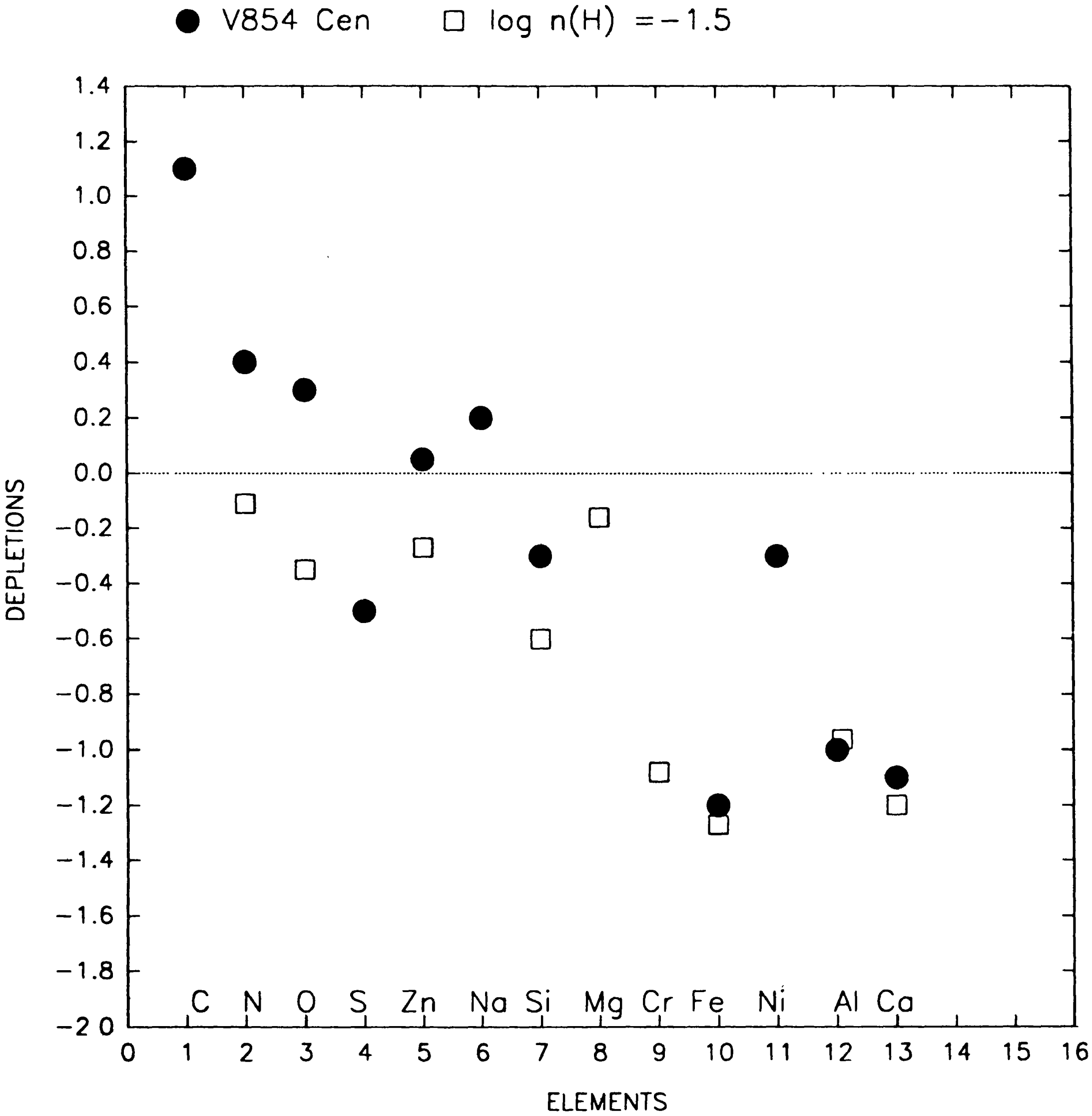

Figure 8. The depletions (w.r.t. solar abundances) of elements in V854 Cen (dots) are shown along with average ISM depletions for $\log n(H_{\rm tot}) = -1.5$ (open squares). Elements are plotted with increasing amount of depletion from left to right.

4.3 *How Were RCBs Formed?*

Schönberner (1986) provides a concise review of the various proposals to account for these H-deficient stars. His preferred method of RCB production involves the merger of two white dwarfs, as advocated initially by Webbink (1984, see also Iben and Tutukov 1984, 1985) and dubbed ‘the double degenerate conjecture’ (here, DD) by Renzini (1990). Renzini’s assessment of evolutionary scenarios leading to RCBs leads him to reject the DD conjecture and to advocate the alternative proposal that the RCB are a class of post-AGB stars that, as white dwarfs, experience a final He-shell flash and are re-inflated briefly to supergiant dimensions (Renzini 1979, 1981; Iben *et al.* 1983). Renzini (1990) dubs this alternative ‘the final helium shell flash conjecture’ (here, FF). Schönberner (1986) discards the FF conjecture on the grounds that the predicted lifetimes of the RCBs are too short ($\tau \sim 10^2$ yr) with respect to the inferred pulsational lifetimes of one (or two!) RCBs. Renzini (1990) tentatively discards the DD conjecture favoured by Schönberner because it appears unable to account for the compositions of the RCBs as known in 1990 from analyses of XX Cam, RCrB and RY Sgr; these three are members of our majority class of 14 RCBs. We comment briefly on the DD and FF conjectures. A third conjecture was discussed by Whitney, Soker & Clayton (1991) who devise a binary model leading to a RCB through two episodes of mass transfer and development of a common envelope for the two stars; this model may not be able to explain why the RCBs belong to a rather old galactic population. We should not preclude the possibility that two (or more) evolutionary paths may lead to RCBs. In particular, the majority and minority (peculiar RCBs) classes may be produced in different ways. Separate evolutionary paths from single and double stars to the RCBs could reasonably account for the two classes of RCBs.

Consideration of Table 1 suggests that evolutionary paths responsible for the majority of RCBs should provide for an atmosphere rich in the products of H and He burning with, perhaps, a contribution from the *s*-process. The DD and FF conjectures are broadly designed to meet this requirement. By sharp contrast, if the low Fe abundance of the peculiar RCBs is accepted as the initial abundance, the evolutionary paths must account for the synthesis of considerable amounts of intermediate elements Na–Ca (He, C or O burning?). Neither the DD nor the FF conjecture as presently sketched, account for production of intermediate elements.

The DD conjecture: This supposes that the immediate progenitor of a RCB is a close pair of white dwarfs: a He white dwarf and a C–O white dwarf. The pair is imagined to have evolved from a pair of main sequence stars via mass transfer and a common envelope phase. Emission of gravitational wave radiation forces a merger of the white dwarfs. Accretion of the He-rich white dwarf by the C–O white dwarf produces a He-rich supergiant with a lifetime of 10^4–10^5yr. The basic features of the composition of the majority class of RCBs are explained qualitatively as follows:

- Accretion of the lighter He white dwarf by the C–O white dwarf provides an N-rich (also Na and Al-rich) He atmosphere;
- A thin layer of unburnt layer of H may reside on the surface of the He white dwarf and this is transferred as an RCB is made;
- As accretion proceeds, shear mixing at the surface of the C–O white dwarf may add C and O to the envelope of the RCB.

Perhaps, it is more difficult to account for the Li-rich RCBs. The DD conjecture matches the observational constraint that RCBs may not be rich in ^{13}C; this constraint is strongest for the HdCs for which $^{12}C/^{13}C \gtrsim 100$ (Climenhaga 1960; Fujita & Tsuji 1977). Another problem which crops up for the DD conjecture is that of the metallicity of stars. As questioned by Hill (1986) the period of coalesence by gravitational wave radiation is expected to be long, about 10^{10} years, the stars thus are expected to be generally metal poor contrary to our present finding of solar metallicity to majority of stars. It is also not clear in DD conjecture how to account for the presence of nebulosities seen around several stars as described in section 2. It remains to be shown that the DD conjecture can account for the observed number of galactic RCBs.

The FF conjecture: After severe mass loss, a red giant leaves the AGB to evolve at constant luminosity to the white dwarf cooling track. If the post-AGB star burns H at the base of the thin H star, the H ash increases the mass of the He shell around the C–O core. Then, the He shell may ignite for a final flash when the star is on the cooling track. Renzini (1990) sketches how this flash may convert the white dwarf to a RCB star. He enlivens his discussion with back-of-the-envelope calculations (and references). The following is a crude summary of the conversion:

- The convective He shell quickly ingests the thin H layer and H is burnt at a temperature of about 10^8 K;
- Energy released by H-burning inflates the mixed thin H–He layer on the white dwarf to a supergiant;
- The energy is stored as gravitational potential energy and subsequently radiated away to return the RCB to the white dwarf cooling track.

Since this supergiant's atmosphere contains products of severe H-burning and of He-burning, the scenario seems a viable way to create H-poor C-rich stars with a high N abundance and an enrichment of Na and Al. Renzini notes that Li production is possible too. The H layer will contain:

^{3}He produced by the main sequence star. Synthesis of ^{7}Li form ^{3}He may occur through the ^{7}Be-transport mechanism (Cameron & Fowler 1971): $^3\mathrm{He}\,(\alpha, \gamma)\,^7\mathrm{Be}(e^+\nu)^7\mathrm{Li}$. On the scoreboard for the FF vs DD game, Renzini cites ^{7}Li synthesis as a point in favour of the FF conjecture; ^{7}Li may not be so easily produced by the DD conjecture.

A potential failure of the FF conjecture, according to Renzini, is that the H-burning results in a low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio for the RCB star. This is in conflict with the observations of RCB and HdC stars. Renzini argues, however, that the ^{13}C nuclei may be largely burnt near the hot base of the He shell. The reaction $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ destroys ^{13}C and releases neutrons. (The reader is referred to Renzini's discussion for an explanation of how ^{13}C may be destroyed but ^{14}N preserved). The neutrons run an *s*-process in the presence of the poison ^{14}N. If the neutron flux is not very high, Y but not Ba may be produced.

Recall that Schönberner (1986) discarded the FF conjecture on the grounds that the resulting RCB has a very short lifetime. Renzini (1990) argues that the lifetime is acceptably long provided that the post-AGB star has a sufficiently low mass. Potential tests of the FF conjecture are noted by Renzini: "a large $^{15}\mathrm{N}/^{14}\mathrm{N}$ ratio may result" and "the less uncertain prediction of the FF conjecture is that a great deal of star-to-star variations in the surface abundances are instead to be expected". Since the RCBs with a quasi-solar Fe abundance, the majority of 14, show little variation in abundances, should we reject them as products of an FF? On the other hand the presence of nebulae can be easily accounted for (or even expected to be present) in FF conjecture.

As noted earlier, the DD and FF conjectures as presently conceived cannot account for the peculiar RCBs with their high Si/Fe and other ratios. (The majority of RCBs may be mildly enriched in intermediate elements Na–S.) One wonders if He, C or O burning can be made a part of the DD conjecture under some conditions: accretion of the He white dwarf heats the C–O white dwarf to the ignition point? Can ingestion of the H layer into the He shell drive a kind of *rp*-process to synthesis of Na–Ca?

It is to be hoped that more detailed calculations of the predicted compositions resulting from the DD and FF conjectures will be attempted soon.

5. Concluding remarks

A biography of Edgar Allan Poe by Silverman (1991) provided the first author of this review with enjoyment on the long flight to India this summer. In April 1841, Poe published "a tale of ratiocination" titled 'The Murders in the Rue Morgue'. With this tale, Poe invented the murder mystery as a form of fiction. In earlier publications such as 'The Fall of the House of Usher' Poe had shown his mastery of tales of horror. Unravelling the compositions of the RCBs and tracing the genealogy of these dying stars could be considered the astrophysical equivalent of a murder mystery. We leave the reader to decide whether the story of the RCBs with their highly unusual chemical compositions should be classified as a 'murder mystery' or 'a tale of horror'! Whatever the classification, we hope that the inventory of 'mere facts' is now significantly more complete and that we are closer to 'the comprehensive truth' about these fascinating stars.

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