

# R CORONAE BOREALIS STARS

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**Abstract.** The R Coronae Borealis stars (RCB) stars are one of the longest known classes of variable star. They fade dramatically and unpredictably by factors of up to one thousand within a few weeks. Over succeeding months, they gradually recover their original brightness. This spectacular fading is caused by the formation of sooty dust clouds above the surface of the star. The surfaces of RCB stars are unusually poor in hydrogen, and rich in carbon and nitrogen, which implies that they are the remnants of evolved stars. Practically all RCB stars pulsate, which may help to explain the dust formation episodes. However, many questions remain regarding their evolutionary origin and the physical mechanism of dust formation.

This article was written with the non-specialist astronomer in mind – particularly because RCB astronomy is one area where amateur observers continue to make an invaluable contribution. It reviews the historical context and the major properties of RCB stars, their physical characteristics and evolutionary status. It introduces a number of related objects and describes some of the unsolved problems still posed by RCB stars.

## 1. INTRODUCTION

R Coronae Borealis stars, or RCB stars, are an important class of variable star. Stars vary in many different ways, often by changing the amount and colour of the light they emit. They can change regularly or irregularly. RCB stars, remarkably, do both.

RCB stars are best known because of their irregular ‘fades’. Unpredictably and every few years or so, their brightness suddenly drops by a huge amount. Then they get slowly brighter until they look the same as before the fade. The fades are caused by enormous clouds of dust which cover a large part of the star’s surface. The dust is thought to be made of small particles of carbon – rather like ground-up pencil sharpenings.

Why the dust clouds form is harder to understand. As well as irregular fades, the light output from RCBs goes up and down by a few per cent every 40 days or so. This is due to the star swelling and shrinking – known as pulsation. It

seems that these pulsations may cause dust to form which is then thrown out from the star. Thus, indirectly, they may be responsible for the irregular fades.

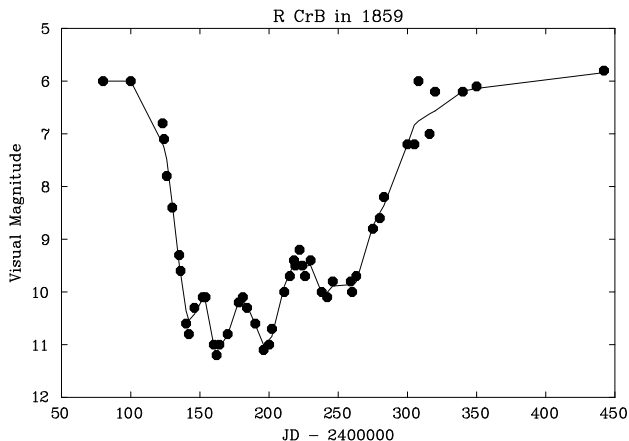
Another remarkable thing about RCB stars is that their surfaces contain almost no hydrogen, the most common element in space. In fact, they are mostly made of helium and carbon. These elements are made by nuclear reactions deep inside stars. Since they are now seen on the surface, RCB stars must be very old.

This article is based on one written for the Encyclopedia of Astronomy & Astrophysics (Murdin 2000), with additional references and other details. It aims to introduce the history and basic observations of RCBs, before exploring their properties in more detail, and is intended for a general audience. Three brief sections address the origin of RCBs, the occurrence of RCB activity in other stars, and recent progress towards solving some of the outstanding problems. Together with an accompanying article on ‘extreme helium stars’ this article aims to be self contained. Literature citations are provided to encourage further exploration of the subject. A recent and more detailed review has been written by Clayton (1996).

## 2. HISTORICAL BACKGROUND

RCB stars are named after a star just visible to the naked eye in the constellation of Corona Borealis. R CrB was discovered by Edward Pigott (1797), an English amateur astronomer, who had been observing a star in the ‘Northern Crown’ for over a decade. In the spring of 1795 he noticed that it had disappeared, but over succeeding months it gradually reappeared and recovered its original brightness. Pigott estimated a period of 10.5 months for this phenomenon, but he was puzzled that the changes did not repeat themselves precisely.

In fact, unlike  $\delta$  Cepheid and other variable stars known at the time, R CrB’s changes in brightness are irregular and unpredictable. This irregularity has prompted numerous astronomers to observe R CrB so regularly that its light curve has now been monitored continuously for almost two hundred years.



**Fig. 1.** The light curve of R Coronae Borealis during a fading event in 1859

Since 1795, other RCB stars have been discovered and their properties have been carefully observed. The defining property is their characteristic light curve, marked by the irregular fadings first seen by Pigott. In addition, nearly all RCB stars pulsate with periods between 40 and 100 days. Their surfaces contain very little hydrogen, unlike the vast majority of stars which have about 90% hydrogen. Instead their surfaces are rich in helium and carbon, which must have been produced by nuclear reactions deep within the star.

It has been established that the sudden fadings of RCBs are caused by clouds of carbon-rich dust passing in front of the star, but it is unclear what causes carbon gas in the stellar atmosphere to condense into dust. Other questions remain about the precise composition and origin of RCB surfaces.

Remarkable as their properties are and extensive as two centuries of observations have been, RCB stars continue to pose many problems. The irony is that the original question posed by Pigott's observations in 1795 remains essentially unsolved – “what causes the sudden fadings of R CrB ?”

### 3. BASIC PROPERTIES

RCB stars were first identified by their characteristic light curves. A part of the light curve of R CrB itself, taken from over a century of observations compiled by Ludendorff (1906) is shown in Figure 1.

#### 3.1. Spectrum

Many light-curve identifications were made retrospectively from photographic plates originally obtained to patrol the sky for asteroids, supernovae and other variable phenomena. As a consequence the light curves were often incomplete so that symbiotic, cataclysmic and semi-regular variables were sometimes identified as RCBs.

RCB stars have a spectrum which resembles that of an F or G supergiant. The Balmer lines of hydrogen are unusually weak or absent, there are many lines of neutral atomic carbon and strong bands of molecular carbon ( $C_2$  and CN). In one of the earliest analyses of stellar surface composition, it was shown that R CrB itself was extremely hydrogen-deficient (Berman 1935). These characteristics have enabled the identification of 34 RCB stars in the Galaxy to be confirmed (cf. Clayton 1996, Jeffery et al. 1996).

There is a small group of early-type stars reputed to show RCB-type light curves and also have weak Balmer lines. These hot RCB stars will be discussed later.

#### 3.2. Galactic distribution and absolute magnitudes

The distribution of galactic RCB stars is controversial. Several authors have argued that they belong to a thick galactic disk, and are thus old Population I stars. The evidence is their scale height in the Galaxy (400pc, Iben & Tutukov 1985). However, their distribution and space velocities suggest they may alternatively belong to the even older galactic bulge (Population II, Drilling 1986). The controversy may simply be a result of the different ways in which surveys for RCB stars and related objects have been carried out. In either case, the populations are sufficiently old that RCB stars must have relatively low masses ( $\leq 1M_{\odot}$ ).

A growing number of RCBs has been discovered in the Large Magellanic Cloud (LMC), most recently as a result of wide field surveys (Alcock et al. 1996). These are the only RCB stars for which a distance is known and hence for which an absolute magnitude can be deduced. With  $M_V \sim -4$  to  $-5$ , the LMC RCBs are 3 000 – 10 000 times more luminous than the Sun (Feast 1979)

#### 3.3. Numbers and distances

The absolute magnitude of the RCBs in the LMC and the small number of Galactic RCBs implies that they are very rare stars. Together with statistics for related stars, the total number of hydrogen-deficient stars in the Galaxy is estimated to be about 1000 (Warner 1967). Whilst the luminosity of RCBs is similar to that of other low-mass stars as they evolve rapidly from the asymptotic giant branch to become white dwarfs, their frequency is much lower. They do not, it seems, represent a stage in the evolution of all normal low-mass stars.

From the preceding estimates of mass and luminosity, it is seen that RCBs have very high luminosity-to-mass ratios ( $L/M \sim 10\,000$ ) and lie close to the Eddington limit for radiative stability. If they were any more luminous, their atmospheres would be expelled by radiation pressure.

## 4. PHYSICAL CHARACTERISTICS

### 4.1. Atmospheres

The fundamental properties of RCBs may be deduced from their spectra at maximum light. A spectrum represents the overall distribution of flux with energy (or wavelength). The properties of a stellar atmosphere may be measured from both the large-scale features – the broad-band flux distribution – and the detailed spectrum of absorption lines. Properties of interest are the effective temperature and the gravity at the stellar surface (these also provide a measure of the luminosity to mass ratio) and the chemical composition. The former can be compared with models for stellar structure and evolution, whilst the composition may provide clues to the past evolution of the star.

RCB effective temperatures fall mostly around 7 000 K, although a small number are as cool as 5 500 K (Kilkenny & Whittet 1984, Asplund et al. 1996). The surface gravities are also low, confirming that RCBs have high  $L/M$  ratios, as suspected from the LMC observations. The spectra of most RCBs have now been analyzed in detail (Asplund et al. 2000). They show that, in general, hydrogen makes up less than one part per thousand down to less than one part per million of the stellar atmosphere. Most of the atmosphere is neutral helium. Although carbon is enriched, it is not possible to establish its abundance reliably. All RCB atmospheres show products of hydrogen- and helium-burning nucleosynthesis in several different episodes. They also show mild enhancements of s-process elements; these are elements formed as a result of certain nuclei being bombarded by neutrons while the star was a red giant.

The broad-band flux distributions of RCBs show an excess amount of flux at low energies. This ‘infrared excess’ corresponds to cool material with a temperature of a few hundred degrees Kelvin which surrounds the star (Kilkenny & Whittet 1984, Walker 1985).

### 4.2. Pulsations

Most RCB stars are small-amplitude variables at maximum light. Light variations are typically a few tenths of a magnitude with periods between 40 and 100 days. In well-studied cases, radial-velocity variations have been found with amplitudes proportional to the light variations. The visual light curve of RY Sgr (period  $\sim 38$  days, amplitude 0.2–0.3 mag.) correlates well with the radial velocity curve (amplitude  $40 \text{ km s}^{-1}$ ) and indicates that RCBs are radially pulsating stars (Alexander et al. 1972).

The light curves of RCB stars are not strictly periodic. Some authors suggest that this is due to interference between a number of radial modes with different periods (Marraco & Milesi 1982, Kilkenny 1982, Lawson & Cottrell 1988, 1990). Since pulsation periods are directly related to the mean density of a star, ev-

idence for period changes were thought to imply secular changes in RCB radii (Kilkenny 1982). More recent work suggests that the changes in period are random (Lombard & Koen 1993). The author believes that this is likely because the extreme non-adiabaticity in the stellar envelope can lead to chaotic behaviour in the pulsation cycle length (cf. Jeffery 2000). More detailed models are needed to test this (cf. Saio & Wheeler 1985).

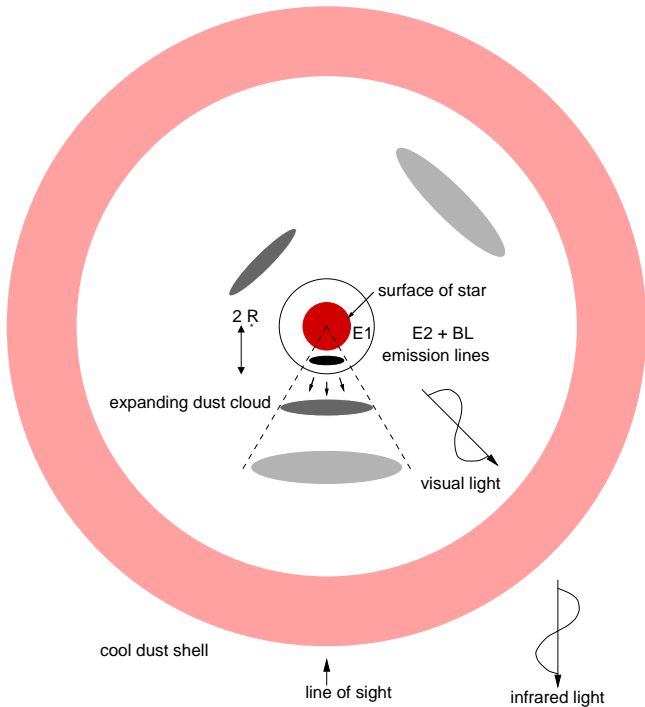
The driving mechanism for pulsations in RCB stars is not the classical  $\kappa$  mechanism found in  $\delta$  CEPHEID VARIABLES; RCB stars do not lie in any of the classical instability strips. Their pulsations are due to ‘strange-mode’ oscillations (Saio et al. 1984). Such pulsation modes are also seen in other high luminosity stars, such as luminous blue variables and  $\alpha$  Cyg variables. Their properties are summarized in the accompanying article on extreme helium stars (Jeffery 2000).

A consequence of the high  $L/M$  ratios of RCB stars is that densities in their atmospheres are low. The action of the pulsations on the photosphere resembles that of a piston imparting an outward impulse at regular intervals. In between these impulses the photosphere is virtually in free-fall. During the impulse, highly non-linear processes can generate shock waves within the photosphere. Evidence for such non-linearity has been observed in RY Sgr where, at minimum radius, absorption lines are seen to double. A red-shifted component is due to infalling material and a blue-shifted component is due to lower-lying plasma that has already been accelerated outwards (Danziger 1963, Lawson et al. 1991). Strong shock waves are expected from theoretical models of pulsations in RCB stars (Saio & Wheeler 1985).

### 4.3. Frequency of fading events

The most obvious and spectacular properties of RCB stars are their dramatic fading events. They spend the majority of their time at maximum light. Initial decline is sudden and steep, the star can fade by up to 8 magnitudes in a few weeks. The decline may show a series of standstills, partial recoveries and subsequent declines. The final recovery to maximum light may take several months to a year. This aspect of RCB behaviour represents an area where amateur astronomers consistently make a major contribution – particularly by alerting the research community to the onset of a fading event. Finding charts and up-to-the-minute light curves are provided online by, for example, the American Association of Variable Star Observers (<http://www.aavso.org/>), or the Variable Star section of the British Astronomical Association Variable Star Section (<http://www.telf-ast.demon.co.uk/>).

The first outline of a mechanism for the fading events was proposed in the 1930’s when it was “shown that the shape of the light curve of R CrB and its spectral variations at minimum can be accounted for by supposing it to eject matter which condenses at a considerable distance



**Fig. 2.** RCB dust-cloud ejection and evolution (based on a figure by Clayton 1996). If a dust cloud is ejected in the line of sight it initially obscures the star, then becomes more transparent as it expands. The outer cool dust shell is regularly replenished by these ejected clouds. It re-radiates stellar flux in the infrared, so that even when the star is obscured in the line of sight, the shell continues to reflect the pulsations at the stellar surface.

and forms obscuring clouds. The solid matter is believed to be principally carbon” (O’Keefe 1939).

From nearly two centuries of observations of RCrB, a characteristic interval of 1100 days between fading events has been deduced (Feast 1986). Several searches have consistently failed to find any regular patterns in RCB declines which might help to identify a causal factor such as rotation or binarity (e.g. Sterne 1935, Howarth 1977, 1978, Dick & Walker 1991, Clayton et al. 1993). For two cases only, RY Sgr and V854 Cen, it has been shown that the onset of the decline episodes may be closely correlated with a particular phase of the pulsation cycle (Pugach 1977, Lawson et al. 1992). It is attractive to relate the onset of a dust formation episode to the pulsation of the stellar envelope, but the evidence for such a connection is not yet compelling.

The ratio between the characteristic interval between fades, and the typical pulsation period of RCBs implies that a decline occurs about once every twenty pulsation cycles (Feast 1986).

#### 4.4. Anatomy of a decline

Infrared observations of RCBs show that, even at maximum light, there are copious amounts of dust surrounding the star (Kilkenny & Whittet 1984, Walker 1985). A very interesting result is that during a decline, when the V-band brightness is plummeting, the infrared L-band brightness shows no significant change and continues to show pulsational variations Feast et al. 1997. It seems that the V-band brightness is dominated by the obscured atmosphere, but the L-band brightness is dominated by dust surrounding the star at some distance. Evidently the dust continues to be illuminated by light from the photosphere, including its pulsations, whilst light coming directly from the photosphere to the observer is obstructed. Therefore the obscuring dust can only cover a fraction of the stellar surface.

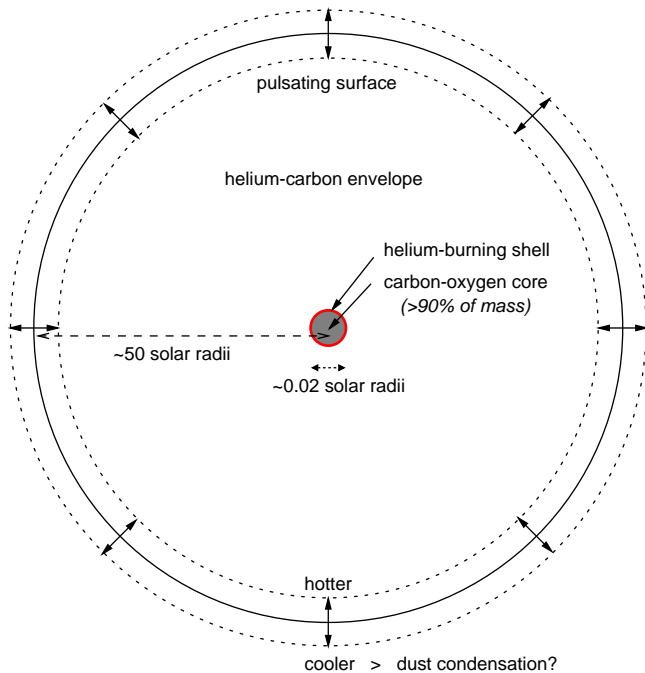
The picture that emerges was first proposed by Loreta (1934) and O’Keefe (1939) (Fig. 2). It now seems clear that at a particular phase in the pulsation cycle, conditions in the photosphere can compel the carbon-rich gas to be expelled from a part of the stellar surface. This gas cools, condenses, and forms dust grains, which are very good at absorbing light from the star. Roughly once every twenty cycles, this ‘puff of soot’ is directed into our line of sight, and obscures the photosphere from view.

Another important observation associated with RCB declines is that, during the early part of the decline, a rich emission spectrum appears, consisting of many narrow lines of neutral and singly-ionized metals (Payne-Gaposchkin 1963, Alexander et al. 1972). These lines (known as E1 lines) appear to be short-lived so that within two or three weeks, they are replaced by a simpler broad-line spectrum (BL), although a few narrow lines (E2) persist for an extended period. The E1 spectrum is probably due to hot gas close to the stellar surface which is visible only when the photosphere alone is obscured. As the dust cloud moves away from the stellar surface it expands, obscuring the E1 region. Since the E2 and BL regions remain visible, they must arise from cooler gas spread over a much larger volume around the star.

This picture of clouds of dust ejected by the pulsating stellar surface has been successful in explaining many properties of RCBs. There remain a number of difficult questions, the hardest being “What is the origin of RCB stars?”

## 5. THE EVOLUTIONARY STATUS OF RCBs

Nuclear processes within stars first convert hydrogen to helium, then helium to carbon, and eventually to heavier elements. RCB surfaces consist primarily of a mixture of helium and carbon-rich layers, with a trace of hydrogen. Single-star evolution does not normally succeed in mixing such different layers of a star, so special models have been proposed to explain their origin.



**Fig. 3.** Internal structure of an RCB star

In one model, a low-mass star which has finished its evolution as a red giant contracts to become a white dwarf, passing through a phase when it illuminates a planetary nebula. It may happen that sufficient unprocessed helium remains on the surface of the white dwarf that nuclear reactions can be reignited. The star then expands suddenly to become a helium-burning red giant for a second time. Convection will thoroughly mix the outer layers of this star to give the mixture of helium and carbon seen in RCBs. This model is sometimes known as the Final Flash (FF) or last thermal pulse (LTP) model (Iben et al. 1983).

In another model, it is supposed that two white dwarfs are in orbit around one another. Over a long timescale ( $\sim 10^{10}$  years), either gravitational radiation or magnetic braking will make the orbit decay and the stars will spiral in towards one another. If one star is a helium white dwarf (HeWD), and the other a carbon/oxygen white dwarf (COWD), the HeWD will be cannibalized by the more massive COWD. This helium will be capable of initiating new nuclear reactions and, like the previous model, the star will expand to become a helium-burning giant, with a helium- and carbon-rich surface. This model is sometimes known as the Double Degenerate (DD) or Merged Binary White Dwarf (MBWD) model (Webbink 1984, Iben & Tutukov 1984).

It is difficult to resolve which model is correct, if either, because RCBs show a range of surface compositions, and the crucial carbon abundance is not well known. However it is agreed that RCBs probably have a degenerate carbon-oxygen core containing upwards of 90% of the mass of the star. Their energy comes from a nuclear-burning shell at the bottom of a tenuous helium-carbon envelope (Fig. 3).

Whilst the core has a radius of approximately  $0.01R_{\odot}$ , the star has an overall radius of some  $50R_{\odot}$ .

## 6. OTHER HYDROGEN-DEFICIENT STARS

### 6.1. Wolf-Rayet stars and hydrogen-deficient binaries

The Galaxy hosts a variety of other extraordinary stars with little or no surface hydrogen. Most are rare, but nevertheless intriguing. Massive Wolf-Rayet stars are young (Population I) hydrogen-deficient stars (Hamann 1996), as are binary systems such as  $\nu$  Sgr (Jeffery 1996).

### 6.2. Hydrogen-deficient carbon stars

Low-mass stars like the RCBs belong to an old population. A group of hydrogen-deficient giants with spectra similar to RCBs show no RCB fading events (Warner 1967). These may have failed to become RCB stars because their luminosities are too low. They are often referred to as 'hydrogen-deficient carbon stars' (HdCs), although this is more by accident than design. The term was originally introduced to represent all of the RCBs, extreme helium stars (see below) and the 'failed' RCBs, since all are hydrogen-deficient and carbon-rich. The HdCs appear to show small-amplitude light variations probably due to pulsation (Lawson & Cottrell 1997), but no ejected debris shows up as an infrared excess (Walker 1985, 1986) or an emission-line region (Brunner et al. 1998).

### 6.3. Extreme helium stars and hot RCB stars

As well as RCB stars with F- and G-type spectra, the 'extreme helium stars' (EHes) are low-gravity A- and B-type stars with weak or no Balmer lines, strong neutral helium and ionized carbon lines (Jeffery 2000). Two of these, MV Sgr and DY Cen, are thought to show RCB-like activity, although they are not very active. The surface carbon abundance of DY Cen is  $\sim 1\%$  by number, the remainder being predominantly helium (Jeffery & Heber 1993). MV Sgr, on the other hand, appears to be quite carbon-poor in comparison with most EHes (Jeffery et al. 1988). A more active B-type helium star, V348 Sgr shows strong emission lines at all times, and has a surface carbon abundance of  $\sim 10\%$  by numbers (Jeffery 1995).

### 6.4. Hydrogen-deficient central stars of planetary nebulae

V348 sgr may be more closely related to about twenty hydrogen-deficient central stars of planetary nebulae which have similar carbon abundances ( $\sim 10\%$ ) and strong emission line spectra (Leuenhagen et al. 1995, Leuenhagen & Hamann 1997). These stars are all overluminous and have strong stellar winds, which give rise to Wolf-Rayet type spectra. Hydrogen-deficient and carbon-rich knots are seen in the inner nebulae of at least two objects (Abell 30 and Abell 78). Such knots may form in

the stellar winds and from time to time give rise to RCB behaviour (Lawson & Jones 1992).

### 6.5. Carbon stars

True ‘carbon stars’ are very cool supergiants with carbon-rich spectra. They are not thought to be particularly hydrogen-deficient, but are low-mass stars which have almost completed their nuclear burning stages. They will soon contract to become a white dwarf, probably illuminating a planetary nebula first. They may provide an important clue to understanding the RCB phenomenon.

Weak RCB-like fading events have recently been discovered in carbon stars (Whitelock 1997), suggesting that the process of carbon condensation is not confined to classical RCB stars. These very large stars also show pulsation-like behaviour with chaotic periods. Recent theoretical work and new observations (Löbel et al. 2000) show that although these pulsations may be ‘radial’, they may not be spherical. Because of the enormous size of these stars, the pulsations may not even be coherent over the whole stellar surface. Thus, as the surface is pushed outwards more over one part of the star than another, that part becomes cooler and less dense. Shocks are more likely to develop and trigger dust condensation over small areas of the photosphere than over the whole surface. In carbon stars, these events may be very localized, obscuring only a fraction of the stellar surface. RCB stars, on the other hand, are not so large as the carbon stars ( $\sim 50 R_{\odot}$  compared with  $\sim 1000 R_{\odot}$ ). As a ‘puff’ is ejected from the star and expands outwards, it is more likely to obscure the whole star while it is still opaque than it would if it were a carbon star.

Detailed numerical modelling of RCB pulsations will be needed to determine whether their pulsations could be aspherical. It is conceivable that careful polarimetric observations over several pulsation cycles might also detect such asymmetries.

### 6.6. Born-again stars

During the past century, three stars have been observed as being both hot subdwarfs and RCB stars at different times.

V605 Aql is now the hydrogen-deficient central star of a planetary nebula (Abell 58). In 1919 it brightened as a slow nova, and there is a report that its spectrum at one time resembled an RCB star (van den Bergh 1971). A hydrogen-deficient knot in the inner nebula could have been ejected around 1919 (Bond et al. 1993).

FG Sge was a faint blue star in 1900. Since then, it has become progressively redder and brighter so that now it has the spectrum of an F or early-G type giant (Herbig & Boyarchuk 1968, Smolinski et al. 1976, Montesinos et al. 1990). Since the 1930s, it has shown somewhat irregular pulsations with a quasi-period increas-

ing from around 5 days in 1934 to about 120 days in the 1990s (van Genderen 1994). In 1992 it started to show RCB type fading events (Jurcsik 1992). Although irregular, their onset appears to occur at a particular phase (light minimum) in the pulsation cycle (Arkipova 1996). At the same time the spectrum has become very carbon-rich (Iijima & Strafella 1993). The surface layers now show the products of many nuclear reaction processes, and are thought to be hydrogen poor (Gonzales et al. 1998). Thus there is evidence to suggest that FG Sge may be a new-born RCB star.

In 1996, an unremarkable faint blue star suddenly brightened and within three years had become a very cool and luminous carbon star, now known as Sakurai’s Object or V4334 Sgr (Nakano et al. 1996, Duerbeck et al. 1997). This star holds the record for being the fastest evolving star known; in addition to its rapid expansion, the surface composition has been observed to change as convection in the stellar envelope dredges more and more processed material from the stellar interior (Asplund et al. 1999). The similarities of some abundance ratios has prompted speculation that V4334 Sgr too may be a new-born RCB star. However its continued evolution to even lower effective temperatures, the development of a high mass-loss rate (Kerber et al. 1999), the presence of a planetary nebula (Benetti et al. 1996) photosphere and the potential emergence of a hot core with a fast wind (Eyres et al., 1999) may equally presage the ejection of new nebula material as the expanding envelope detaches itself from the core, followed by a rapid return to the PN phase.

The spectacular evolution of these three stars has been explained in terms of the final-flash model. Their similarities with RCB stars may eventually help to explain the origin of RCB stars. Alternatively, the fact that V605 Aql contracted to become a hot central star as quickly as it became a giant, whilst R CrB itself has not changed significantly over the last 200 years, may mean that these three stars represent entirely separate evolutionary pathways.

## 7. UNSOLVED PROBLEMS

Since the discovery of RCrB itself, the mechanism that produces fadings has been elusive. Primary data connecting pulsation phase and the trigger for fadings exists for only two RCBs (V854 Cen and RY Sgr, Lawson et al. 1992, Pugach 1977), and protracted photometry of several RCBs will be necessary to establish any connection firmly.

A second difficulty is encountered by the physical conditions necessary for dust to condense above the surface of the star. The frequency and duration of fading events implies a geometry in which the dust clouds form within two stellar radii ( $2 R_{\star}$ , Clayton et al. 1992). Under normal conditions, the local temperature would be too high for dust to condense at this distance, and a condensation distance of  $20 R_{\star}$  would be expected (Faddeyev 1986). Recent

models treat the chemistry, energy balance and dust nucleation in pulsating star atmospheres in considerable detail (Woitke et al. 1996a, 1996b). They show that excess cooling can occur during adiabatic expansion after the passage of a shock wave, reducing the local temperature to about 1500 K within 1.5–3  $R_*$ . It remains to be shown that pulsations in all RCB stars provide the necessary conditions for dust nucleation to occur at this distance.

The RCB carbon abundance remains an enigma (Asplund et al. 2000). If it is  $\sim 1\%$  or  $\sim 10\%$  determines if RCBs are related to the C-rich remnants like the extreme helium stars or to C-strong remnants like the H-deficient central stars of planetary nebulae.

The problem is a natural consequence of stellar atmosphere physics. The strength of a stellar absorption line represents the ratio of line opacity to continuous opacity in the atmosphere; both are related to the number density of the absorbing atoms and so provide the number ratio of line absorbers to continuum absorbers. When the line and continuum absorbers are the same, it becomes impossible to measure the abundance of the absorbing species. In hydrogen-rich stars, hydrogen is normally the main continuum absorber, and since it is also assumed to be the most abundant species, the problem does not arise. Since the predominant continuum absorber in RCB atmospheres is neutral carbon, it has not yet proved possible to measure the carbon abundance from carbon absorption lines.

Finally, the emission line spectrum seen during fading events is difficult to explain, especially the sodium D lines which indicate an expansion (or wind) velocity of several hundred  $\text{km s}^{-1}$  (Rao et al. 1999). Superimposed are a number of narrow absorption components, possibly representing cooling gas from previous ejections. The presence of heavily blue-shifted absorption from infalling material remains a puzzle.

## 8. Conclusion

RCB stars offer the astronomer a wealth of information, from their spectacular fadings, through their pulsations and dust shells, to the nuclear waste on their surfaces that traces previous evolution. Even with all of these data, RCBs retain much of their original mystery. This review has attempted to give an accurate impression of their overall properties and an insight into some of the physical processes responsible for them. However, the author is generally more familiar with the physics of stellar interiors and hot star atmospheres. Inevitably there will be omissions of important data and contributors, for which the author apologises. The 200-year history of RCB research is wide-ranging and far from over. The task of future reviewers is unlikely to be easier – but our fascination with some of the most unusual stars in the sky is unlikely to diminish.

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