Publications of the
Astronomical Society of the Pacific

Vol. 108 **1996 March** **No. 721**

Publications of the Astronomical Society of the Pacific
108: 225–241, 1996 March

Invited Review Paper

The R Coronae Borealis Stars

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Received 1995 November 3; accepted 1995 December 21

ABSTRACT. This year marks the bicentennial of the discovery of the variability of R Coronae Borealis. The R Coronae Borealis (RCB) stars are distinguished from other hydrogen-deficient objects by their spectacular dust-formation episodes. They may decline by up to 8 magnitudes in a few weeks, revealing a rich emission-line spectrum. Their atmospheres have unusual abundances with very little hydrogen and an overabundance of carbon and nitrogen. The RCB stars are thought to be the product of a final helium shell flash or the coalescence of a binary white-dwarf system. Dust may form in non-equilibrium conditions created behind shocks caused by pulsations in the atmospheres of these stars. The RCB stars are interesting and important, first because they represent a rare, or short-lived stage of stellar evolution, and second because these stars regularly produce large amounts of dust so they are laboratories for the study of dust formation and evolution.

1. INTRODUCTION

The R Coronae Borealis (RCB) stars exhibit some of the most spectacular behavior seen in any class of variable stars. Their atmospheres are extremely hydrogen deficient and carbon rich. They are apparently of low mass yet high luminosity, and at irregular intervals they manufacture thick dust clouds which can completely obscure the photosphere of the star. During these dust formation episodes, the brightness of the star can decrease by up to 8 magnitudes in a few weeks revealing a rich emission-line spectrum. Perhaps because of this, RCB stars attracted early attention from astronomers. It is exactly 200 years since the prototype of the class, R Coronae Borealis, previously observed to be about 6th magnitude, was discovered to be missing from the sky (Pigott 1797). R CrB reappeared later in 1795, returning to maximum light only to fade again. In 1890, Espin, observed large changes in the strength of the Swan bands of C_2 in R CrB (see Berman 1935). And just after the turn of the century, the absence of H γ and the G-band in the spectrum of R CrB was noticed (Ludendorff 1906; Cannon 1912). However, it was not until the comprehensive spectroscopic study of Berman (1935) that it was accepted that the reason for the weak Balmer lines was hydrogen deficiency (Bidelman 1986). The emission lines associated with RCB star declines were first studied by Joy and Humason (1923). The generally accepted model for dust formation was suggested over a half a century ago (Loreta 1934; O'Keefe 1939). As O'Keefe says, "It is shown that the shape of the light curve of R Coronae Borealis and its spectral variations at minimum can be accounted for by supposing it to eject matter which condenses at a considerable distance and forms obscuring clouds. The solid matter is believed to be principally carbon." Even now, after two centuries of observation, many aspects of the RCB phenomenon remain mysterious including the details of the dust formation mechanism, the evolutionary status of RCB stars and the nature of their emission-line regions.

There has not been a general review on the subject of RCB stars for twenty years (Feast 1975), although there have been valuable reviews of various aspects of these stars (Feast 1979, 1986, 1990, 1996; Lambert 1986; Walker 1986; Fadeyev 1986; Hill 1987; Efimov 1988; Renzini 1990; Lambert and Rao 1994; Jeffery 1994). When the last general review was written, only three major spectroscopic studies of RCB star declines had been published (Herbig 1949; Payne-Gaposchkin 1963; Alexander et al. 1972). The available observational database has increased greatly in the last two decades particularly at UV and IR wavelengths. Spectroscopic data from several additional declines have been published (e.g., Cottrell et al. 1990; Clayton et al. 1992a,b, 1993a, 1995a; Lawson 1992; Rao and Lambert 1993a,b). Even now, spectroscopic data are only available for the three brightest RCB stars, R CrB, RY Sagittarii, and V854 Centauri. In addition, much IR and visible photometry, and polarimetry of declines have been obtained (e.g., Feast et al. 1977; Menzies 1986; Feast 1990; Clayton et al. 1995b).

In this review I will attempt to summarize the available observational data, analysis, and modeling to give a picture of our present understanding of these enigmatic stars.

2. HOW MANY RCB STARS?

The hydrogen-deficient stars also include the extreme helium (EHe) stars and the hydrogen-deficient carbon (HdC) stars. These stars are all supergiants ranging in spectral type from B to G with very little hydrogen in their atmospheres. The HdC stars are distinguished from the RCB stars by the absence of large-scale variability and IR excesses. The EHe stars are hotter and with the exception of three RCB-like stars do not show large-scale variability. Four of the EHe stars are spectroscopic binaries. These stars, the so-called hydrogen-deficient binaries, differ from the single EHe stars in that they have a much higher nitrogen-to-carbon abundance (Drilling 1986). The binaries are thought to be young Population I stars unrelated to the other hydrogen-deficient stars. None of the HdC or RCB stars is known to be binary. Several RCB stars have close companions although no physical connection has been established (Milone 1995). At least some of the EHe stars and all RCB stars seem to be pulsational variables (Lawson and Kilkenny 1996).

Despite their eye-catching lightcurve and spectral behavior, the number of known RCB stars is small. The *General Catalog of Variable Stars* (GCVS) lists 26 stars as RCB (Kholopov 1985). Other recent lists of RCB and HdC stars are contained in Bidelman (1979) (45 stars), and Drilling and Hill (1986) (29 stars). The most recent list of known or suspected RCB stars contains 40 stars (Milone 1990). Outside the Galaxy, only 3 RCB stars, all members of the LMC, are known (Feast 1972). Until recently, many stars designated RCB had not been spectroscopically verified. Many turn out to be symbiotic, cataclysmic, or semi-regular variables (Lawson and Cottrell 1990a). Much of this sorely needed spectroscopic work has been performed by Kilkenny and collaborators (see references to Tables 1 and 2). New data since 1990 concerning the identification of these stars are summarized in Tables 1 and 2. Stars believed or suspected to be RCB stars are listed in Table 1. Table 2 lists stars previously thought to be RCB stars but which are now believed to be other types of objects. There are also three hot extreme helium (EHe) stars, MV Sagittarii, V348 Sagittarii and DY Centauri, which show RCB-like behavior. They are included in Table 1. Several interesting objects that may be related to the RCB stars are not included in Table 1. They are:

(a) V605 Aquilae which showed an RCB-like the spectrum during its 1919 outburst. It is the central star of the planetary nebula A58 (van den Bergh 1971; Bidelman 1973; Bond et al. 1993).

(b) η Carinae which in 1893 showed a spectrum reminiscent of an RCB star at maximum light (Bidelman 1993).

(c) FG Sagittae which may be evolving into an RCB phase (e.g., Jurcsik 1993).

TABLE 1
Spectroscopically Confirmed RCB stars

Name	GCVS Type	α(2000)	δ(2000)	Max	Spec. Ref.[1]	Notes[2]
DY Per	SR	02 35 05	+56 09 12	12.6	1,2	*
XX Cam	RCB	04 08 39	+53 21 39	8.7	3,4,5,6,7,8	*
HV 5637	...	05 11 32	−67 56 00	15.8	9,10	*
W Men	RCB	05 26 24	−71 11 12	13.8	9,10,11,12,13,14	*
HV 12842	...	05 45 03	−64 24 24	13.7	10,12,15	*
SU Tau	RCB	05 49 06	+19 04 00	9.5	3.5,9	...
UX Ant	RCB?	10 57 09	−37 23 42	12.2	3,11,16,17	*
UW Cen	RCB	12 43 17	−54 31 42	9.6	3,11,18	...
Y Mus	RCB	13 05 48	−65 30 45	10.5	3,11,19	*
DY Cen	RCB	13 25 32	−54 14 48	12.0	11,20,21	*
V854 Cen	...	14 34 49	−39 33 19	7.0	3,22	*
Z UMi	M?	15 01 31	+83 03 00	11.0	23	...
S Aps	RCB	15 09 24	−72 03 45	9.6	9,11	...
R CrB	RCB	15 48 34	+28 09 25	5.8	3,4,5,12,24,25,26	...
RT Nor	RCB	16 24 20	−59 20 48	11.3	3,11,27	...
RZ Nor	RCB	16 32 36	−53 15 54	11.1	3,11,28	...
V517 Oph	Lb	17 15 20	−29 05 24	12.6	29	...
V1773 Oph	RCB	17 17 22	−20 22 36	16.8	11	*
V1783 Sgr	Lb	18 04 50	−32 43 12	12.5	30	...
GM Ser	RCB	18 08 36	−15 04 00	12.0	11	*
WX CrA	RCB	18 08 52	−37 19 36	11.0	11,27	...
V739 Sgr	Is?	18 13 13	−30 16 16	14.0	30	...
V3795 Sgr	...	18 13 24	−25 46 54	11.5	3,31	*
VZ Sgr	Isa?	18 15 08	−29 42 34	11.8	3.27	*
RS Tel	RCB	18 18 51	−46 32 51	9.3	3.5,11,27	...
GU Sgr	RCB	18 24 15	−24 15 24	11.3	3.11,27	...
V348 Sgr	...	18 40 19	−22 54 31	10.6	27,32,33,34	*
MV Sgr	RCB	18 44 32	−20 57 18	12.0	11,35,36	*
FH Sct	L	18 45 16	−09 25 48	13.4	3.37	...
V CrA	RCB	18 47 32	−38 09 31	9.4	3,11,27	*
SV Sge	L?	19 08 12	+17 37 39	11.5	5	...
V1157 Sgr	M	19 10 12	−20 29 43	12.5	30	...
RY Sgr	RCB	19 16 33	−33 31 19	6.5	3.4,5,38,39	...
V482 Cyg	?	19 59 44	+33 58 30	12.1	3,27,40	...
V1405 Cyg	...	21 57 31	+53 53 42	15.5	11	*
U Aqr	RCB?	22 03 20	−16 37 33	10.5	27,41,42	*
UV Cas	RCB	23 02 13	+59 36 42	11.8	3,27,43	...

[1] Spectroscopic References:
1) Alksnis 1994; 2) Dominy 1985; 3) Lambert and Rao 1994; 4) Cottrell and Lambert 1982; 5) Bidelman 1953; 6) Rao, Ashok, and Kulkarni 1980; 7) Walker 1986; 8) Orlov and Rodriguez 1974; 9) Feast 1972; 10) Feast 1979; 11) Milone 1990; 12) Pollard et al. 1994; 13) Feast 1956; 14) Rodgers 1970; 15) Morgan, Nandy, and Rao 1986; 16) Kilkenny and Westerhuys 1990; 17) Lawson et al. 1994; 18) Giridhar and Rao 1986; 19) Stephenson 1978; 20) Pollacco and Hill 1991; 21) Jeffery and Heber 1993; 22) Kilkenny and Marang 1989; 23) Benson et al. 1994; 24) Berman 1935; 25) Searle 1961; 26) Keenan and Greenstein 1963; 27) Bidelman 1979; 28) Feast 1975; 29) Kilkenny et al. 1992; 30) Lloyd Evans, Kilkenny and van Wyk 1991; 31) Hoffleit 1972; 32) Jeffery 1995; 33) Leuenhagen, Heber, and Jeffery 1994; 34) Dahari and Osterbrock 1984; 35) Jeffery et al. 1988; 36) Herbig 1964; 37) Feast 1992; 38) Danziger 1965; 39) Alexander et al. 1972; 40) Rao and Lambert 1993b; 41) Malaney 1986; 42) Bond et al. 1979; 43) Orlov and Rodriguez 1981

[2] Notes to Table 1

- DY Per: Possible new RCB star. Minima in 1991, 1993 and 1995 (Mattei 1995, personal communication).
- XX Cam: Very inactive. No IR excess. Since 1898, only one small decline ($\sim$ 1.7 mag) (Yuin 1948).
- W Men, HV 5637, HV 12842: LMC stars.
- HV 5637: Infrequent declines and uncertain IR excess (Glass et al. 1994).
- Y Mus: No declines recently but has IR excess (Clayton 1994; Walker 1986).
- DY Cen, MV Sgr, V348 Sgr: Hot RCB stars.
- V854 Cen, V CrA, VZ Sgr, V3795 Sgr, U Aqr: Unusual abundances (Bond et al. 1979; Lambert 1986; Lambert and Rao 1994).
- V1773 Oph, GM Ser, V1405 Cyg: There is no published spectroscopic confirmation of these stars.

TABLE 2
Stars Previously Identified as RCB Stars

Name	GCVS Type	New Type	α(2000)	δ(2000)	Max	Spec. Ref.
DZ And	RCB?	?	00 32 36	+26 01 21	10.0	1,2
SY Hyi	RCB?	SR	02 17 11	−79 25 22	13.4	3
HV 12671	...	Symbiotic	05 48 44	−67 36 13	14.5	4,5,6,7
MT Pup	RCB?	CV	07 54 09	−14 38 42	15.0	8
V803 Cen	...	AM CVn	13 23 45	−41 44 30	13.2	9,10,11,12
Z Cir	RCB?	LPV	13 51 01	−70 28 14	12.0	12,13
V504 Cen	L	CV	14 12 49	−40 21 12	12.0	14
AE Cir	RCB	Symbiotic	14 44 52	−69 23 36	12.2	12,15,16
LR Sco	SR	SR	17 27 56	−43 50 48	10.9	17,18
V731 Sco	RCB?	?	17 33 21	−32 34 12	12.9	19,20
V973 Oph	RCB?	Me	17 37 24	−27 12 48	12.6	19,21,22
V589 Sgr	RCB?	Symbiotic?	18 05 15	−34 44 42	14.2	23
V618 Sgr	RCB	Mira?	18 07 57	−36 29 36	11.0	8
V1860 Sgr	RCB?	?	18 21 28	−24 45 06	13.5	12,19
V433 Cas	M	Mira?	23 25 17	+61 20 00	14.5	24

Spectroscopic References:
1) Orlov and Rodriguez 1975; 2) Rao 1980; 3) Lawson et al. 1989; 4) Lawson et al. 1990; 5) Feast and Webster 1974; 6) Cowley and Hartwick 1989; 7) Allen 1980; 8) Kilkenny 1989b; 9) Elvius 1975; 10) O'Donoghue, Menzies, and Hill 1987; 11) Westin 1980; 12) Milone 1990; 13) Feast 1965; 14) Kilkenny and Lloyd Evans 1989; 15) Kilkenny 1989a; 16) Lawson and Cottrell 1990a; 17) Giridhar, Rao and Lambert 1990; 18) Stephenson 1978; 19) Feast 1975; 20) Paolantonio and Calderon 1993; 21) Feast 1992; 22) Koen, Lloyd Evans and Kilkenny 1995; 23) Kilkenny 1995, personal communication; 24) Rosino, Bianchini, and Martino 1976

(d) The HdC stars which are similar to the RCB stars spectroscopically but do not show declines or IR excesses (Warner 1967). Schönberner (1996) points out that FG Sge is not hydrogen deficient so it is not a good RCB candidate.

The sample, as listed in Table 1, is certainly incomplete. The surveys for RCB stars have been magnitude limited. Consider the case of V854 Cen. This star is the third brightest RCB in the sky at 7th magnitude yet it was discovered only in the last decade (McNaught and Dawes 1986). It was generally fainter than 13th magnitude and no brighter than 10th from 1913 to 1952 so it does not appear in the HD, CPD or SAO catalogs (Wenzel et al. 1986; McNaught 1986).Jomaron et al. (1994) have begun a project to find new RCB stars using *Infrared Astronomical Satellite (IRAS)* colors to select candidates. The MACHO database of LMC fields is also being searched for new RCB stars. Three candidates have been found so far (Clayton 1996, unpublished data).

Hydrogen-deficient stars are very rare. In addition to the RCB stars, there are 20 EHe stars, and five HdC stars known (Drilling 1986). The paucity of HdC stars is no doubt due to the difficulty of recognizing these stars without the large variability which causes the RCB stars to stand out. Taking this into account, there may be up to 1000 HdC stars in the Galaxy (Warner 1967). Beyond their numbers, the distribution of these stars on the sky and their radial velocities give clues to their origin. The space distribution and radial velocities of the HdC and EHe stars are similar to those of distant planetary nebulae implying that these stars are a bulge population (Drilling 1986). However, the five HdC stars have large proper motions, possibly indicating space velocities as high as 400 km s^{-1}, more representative of a halo population (Warner 1967). The distribution and velocities of the RCB stars also tend toward those of the bulge population but the data are not as compelling. In the discussion following Drilling's paper, it is reported that new data show that the radial velocities of the RCB stars are significantly lower than those of the EHe stars. The scale heights for these two groups of stars have been derived as $z=1700$ pc for the EHe stars and 400 pc for the RCB stars (Iben and Tutukov 1985). So while the EHe stars seem to be bulge/Population II stars, the RCB stars may be more like old disk/Population I stars. These data are summarized in Jeffery et al. (1987), who point out that there is a clear division between high and low velocity stars at $T_{\text{eff}} = 12{,}000$ K. There is no known explanation for this apparent correlation between effective temperature and Galactic orbital velocity. However, for the hydrogen-deficient binaries, the scale height is less than 200 pc and the radial velocities strongly imply young disk/Population I stars. The sample of RCB stars is biased toward higher Galactic latitudes but most RCB stars were detected in magnitude-limited surveys so reddened stars in the Galactic plane would have been missed (Lawson et al. 1990; Lawson and Cottrell 1990b). The data on velocities and distributions, although somewhat ambiguous, indicate that the various groups of hydrogen deficient stars may not be closely related.

The distances and absolute magnitudes of RCB stars are completely dependent on 3 stars in the LMC (Feast 1979). Using their apparent magnitudes and the known distance of the LMC, an absolute magnitude of $M_V \sim -4$ to -5 is deduced for the RCB stars. This assumes that all RCB stars, in the Galaxy and in the LMC, have the same absolute magnitude. No distances are known for Galactic RCB stars (See Rao and Lambert 1993b for a discussion). The parallaxes of several RCB stars are being measured as part of the *HIPPARCOS* mission.

3. RCB STARS FROM OBSERVATIONS

From an observational point of view, an RCB star can be identified as having all of the following characteristics:

1. The stellar spectrum looks like an F or G supergiant with anomalously strong carbon, and weak or absent hydrogen absorption features. Three hot RCB stars are known which have B-type spectra.

2. All RCB stars are variable at maximum light, typically with periods of 40–100 days and amplitudes of a few tenths of a magnitude. In most if not all cases, these variations are due to pulsations.

3. Deep declines of up to 8 magnitudes in the visible occur without warning at irregular intervals. The star spends most of its time at maximum light with declines occurring every few years. The decline is sharp. The star typically experiences a drop in brightness of several magnitudes in a few weeks. The star may remain faint for an extended period or have several recoveries and declines in succession. Often the final rise back to maximum light is slow taking several months to a year.

5. As the star fades at the onset of a decline, a rich emission-line spectrum always appears consisting of singly ionized and neutral metals. This narrow-line spectrum fades after a couple of weeks leaving a few broad emission lines, notably, Ca II H and K, Na I D, and Mg II h and k.

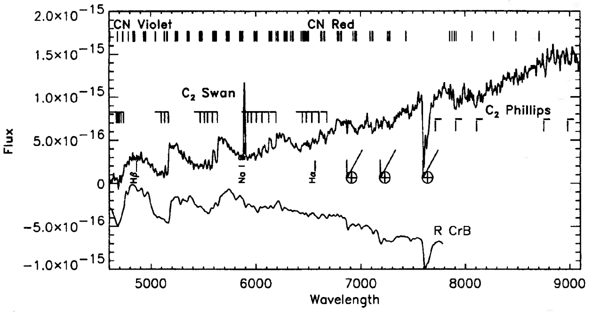

FIG. 1—The spectra of Z UMi (upper spectrum) and R CrB (lower spectrum). R CrB is at maximum light. Z UMi is recovering from a decline but the stellar continuum is visible. The C_2 and CN bands are marked. Strong Na I D emission is seen in Z UMi. (From Benson et al. 1994; © American Astronomical Society, reproduced with permission.)

6. All RCB stars have a near-IR excess due to circumstellar dust. Many are also detected at *IRAS* wavelengths.

3.1 At Maximum Light

3.1.1 Stellar Spectra and Abundances

Early studies of RCB stars at or near maximum light showed that the typical spectrum looks like a F or G supergiant with a few important differences (Berman 1935, R CrB; Searle 1961, R CrB; Keenan and Greenstein 1963, R CrB; Danziger 1965, RY Sgr). The Balmer lines are very weak or absent. The spectrum contains many lines of neutral atomic carbon, and bands of C_2 and CN (see Fig. 1). RCB stars are thought to be slow rotators although there is only one measurement in the literature. For R CrB, Uesugi and Fukuda (1970) find $v \sin i \sim 18$ km s^{-1}. Until recently, high-resolution, fine abundance analyses existed for only 3 RCB stars, R CrB, XX Camelopardalis, and RY Sgr (Cottrell and Lambert 1982a; Schönberner 1975; Jones 1991). Pollard et al. (1994) add to this sample with fine abundances for SU Tauri, HV 12842, and W Mensae. The latter two stars are members of the LMC. Also, Lambert and Rao (1994) report preliminary results on a sample of 18 RCB stars. A good review of the earlier abundance work is contained in Lambert (1986). The RCB stars are characterized by extreme hydrogen deficiency and an overabundance of carbon. In general, C/H $\geqslant 10^3$, [C/Fe] ~ 1, [X/Fe] $\sim$ solar for most other species up to iron-peak elements and $^{12}C/^{13}C \geqslant 100$ (Pollard et al. 1994). Lambert and Rao (1994) with their larger sample find that 14 of 18 RCB stars have quite similar compositions. In this group, only hydrogen and lithium abundances vary strongly from star to star. On average, hydrogen is under-abundant by about 10^5 and carbon is over-abundant by a factor of 10 compared to solar. Nitrogen and sodium are also over-abundant. Among the four RCB stars that have unusual compositions, V854 Cen, V Coronae Australis, VZ Sagittarii, and V3795 Sagittarii, two are relatively hydrogen rich and all are iron poor. They also show high S/Fe and Si/Fe ratios. The hydrogen deficiency for V854 Cen is ~ 0.1 and for V CrA, it is ~ 0.01 (Lambert and Rao 1994). Strong Balmer lines and possibly CH bands are seen in the spectrum of V854 Cen (Kilkenny and Marang 1989; Lawson and Cottrell 1989). The hot RCB star, DY Cen, also has a relatively high hydrogen content (Jeffery and Heber 1993). Another RCB with very unusual abundances, which is not included in the Lambert and Rao sample, is U Aquarii (Bond et al. 1979).

3.1.2 Pulsations

All RCB stars measured thus far seem to be pulsating variables (Feast 1975; Fernie et al. 1986; Lawson et al. 1990, 1993; Lawson and Kilkenny 1996). However, global radial pulsations have been confirmed in only a few stars. In particular, two stars, RY Sgr and V854 Cen, have well-determined regular pulsations of 38 and 43 days, respectively. It has been suggested that similar photometric variations could result from the action of a few large convection cells (Wdowiak 1975; Feast 1996) but it is not clear that the action of these cells would produce the observed brightness and color changes. Long-term photometry on 15 RCB stars is presented and summarized in Lawson et al. (1990, 1994). The periods generally lie between 40 and 100 days. RY Sgr has the best characterized pulsation period of ~ 38 days which is semi-regular in both duration and amplitude. This period is an average period and in any individual cycle, the times between maxima may differ by 20% or more. However, Fourier analysis shows that the pulsations are essentially constant in period and amplitude (Lawson 1996, personal communication). The times of the color maxima lead the light maxima by about 4 days. Several attempts have been made to explain variations in the O−C plane for RY Sgr in terms of a decreasing or regularly varying pulsation period (Marraco and Milesi 1982; Kilkenny 1982; Lawson and Cottrell 1988, 1990c). However, recently Lombard and Koen (1993) find that the observed O−C variations are random. Lawson et al. (1990) found an additional periodicity in RY Sgr of ~ 55 days duration that seems to be irregular in amplitude perhaps due to beating with the 38 day period. Unlike RY Sgr, R CrB does not have a single dominant pulsation period. The light curve of R CrB has been closely followed from 1986 to 1993 (Fernie et al. 1986; Fernie 1989; 1990a,b; 1991; Fernie and Lawson 1993; Fernie and Seager 1994). In addition, fragmentary observations are available from 1971 to 1990 (Fernie 1982; Lawson 1991). Analysis of these data shows that periods of 44 and 52 days are most strongly present with one or the other dominating from year to year. There isn't a long-enough baseline to relate these changes to the variations in dust formation activity. However, there were declines in 1985–86 and 1988–89 around the times where the dominant pulsational periods were switching (Clayton et al. 1995b).

Radial-velocity variations have been studied in detail for only four RCB stars, R CrB, RY Sgr, V854 Cen and UX Antliae (Lawson and Cottrell 1989; Lawson et al. 1991; Fernie and Lawson 1993; Lawson et al. 1994). Lawson and Kilkenny (1996) present preliminary results of a radial-velocity survey of RCB stars. They find typical peak-to-peak variations in radial velocity and brightness to be 10–20 km s^{-1} and 0.2–0.3 mag, respectively. The ratio of radial-velocity amplitude to brightness amplitude increases with temperature. RY Sgr shows the largest radial-velocity varia-

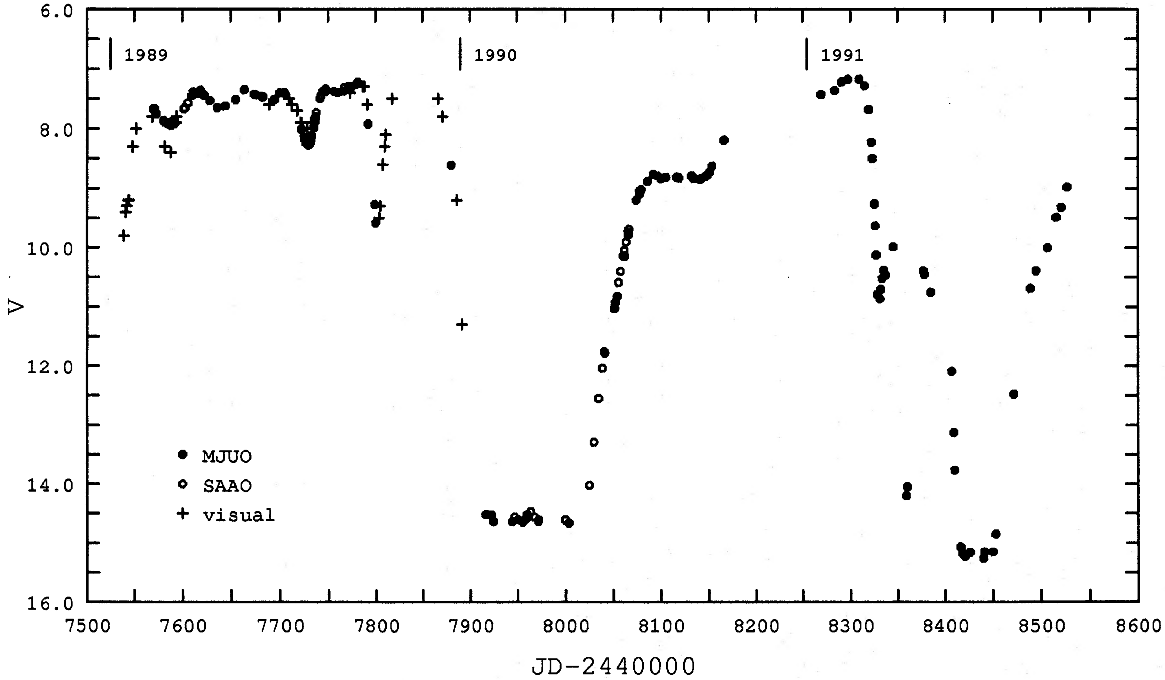

FIG. 2—Light curve of V854 Cen from 1989–1991. Note the frequent occurrence of declines spaced 43 days apart, which are correlated with pulsation phase. (From Lawson et al. 1992; © Royal Astronomical Society, reproduced with permission.)

tions ($\Delta v \sim 40$ km s^{-1}) of any RCB star (Lawson et al. 1991). UV data show a much smaller range of radial velocity variations ($\Delta v \sim 13$ km s^{-1}) (Clayton et al. 1994). The UV-velocity amplitude found for RY Sgr exceeds that observed in R CrB ($\Delta v \sim 6$ km s^{-1}) (Holm and Doherty 1988) by about a factor of 2, roughly the ratio of observed velocity variations in the visible. Fernie and Lawson (1993) point out that the ratio of velocity amplitude to V-band amplitude is similar in both stars. The amplitude of radial-velocity variations in V854 Cen and UX Ant are much smaller.

Line splitting due to photospheric shocks in RY Sgr spectra was first noted by Danziger (1963). The absorption lines split at certain phases, related to the 38 day pulsation period of the star (Cottrell and Lambert 1982b; Lawson 1986; Cottrell et al. 1988; Lawson et al. 1991). Many strong lines are split. Just before the lines split, the spectrum takes on a "washed out" look. Lawson et al. (1991) found that the line splitting event may last 16–20 days (0.4–0.5 of a cycle) after which it returns to normal. The onset of the splitting phase occurs near the $B - V$ maximum. Thus far, this phenomenon has been detected only in RY Sgr which has the most extreme radial-velocity variations among the RCB stars.

3.2 In Decline

3.2.1 The Light Curve

The nature of the visible light curve has been well characterized. Both R CrB and RY Sgr have been monitored for over a century. The historical AAVSO light curve of R CrB from 1843 to 1990 is shown in Mayall (1960), and Mattei et al. (1991). The RY Sgr light curve is shown in Mayall (1972), and Mattei et al. (1993). These light curves are typical of those seen for other RCB stars. The recent light curve for V854 Cen in shown in Fig. 2. RCB stars are true irregular variables. They spend a majority of their time at maximum light with a characteristic time between declines of about 1100 days (Feast 1986). The initial decline is sudden and steep, and the brightness of the star can drop by up to 8 magnitudes in a few weeks. The decline is often characterized by a series of standstills, partial recoveries and subsequent declines, followed by a final slow recovery to maximum light. The rises and falls in brightness to local maxima and minima during a particular decline are often as steep as the initial decline and occur on time scales of about a month. During the final recovery, the star may take months or years to return to maximum light. Each successive drop in brightness within a decline is caused by new dust formation. These episodes of dust formation often seem to occur on successive pulsation cycles of the star. This can be seen for V854 Cen in Fig. 2.

There have been many searches for regular patterns in RCB declines (Sterne 1935; Lukatskaya 1975; Tempesti and De Santis 1975; Howarth 1977, 1978; Goncharova et al. 1983; Rosenbush 1986; Percy et al. 1987; Dick and Walker 1991; Clayton et al. 1993b). If dust formation is related to stellar rotation or some kind of binary interaction, then declines might occur at regular intervals. These studies are in agreement that those RCB stars (R CrB, RY Sgr, SU Tau, S Apodis) which have been followed for long periods of time, experience declines at irregular intervals.

Strong evidence for a physical connection between the RCB star and the condensing dust comes from the correlation between pulsational phase and the time of decline onset found for RY Sgr and V854 Cen which show fairly regular pulsation cycles of 38 and 43 days, respectively (Pugach 1977; Lawson et al. 1992). As can be seen in Fig. 2, the light curve of V854 Cen in 1990–91 experiences several successive declines separated by about 43 days (Lawson et al. 1992). Pugach (1977) and Goncharova et al. (1983) find that fadings of R CrB tend to begin in a restricted range of phase from statistical studies of observed fadings. Goncharova et al. (1983) and Goncharova (1985; 1989) found that the declines of R CrB are locked to three different periods. However, more recent studies find no significant correlation (Percy et al. 1987; Lawson 1991; Fernie and Seager 1994). Another possible connection with dust formation and pulsations is seen in bandstrength variations of C_2 and CN which are correlated with pulsational phase in R CrB (Clayton et al. 1995b) and RY Sgr (Lloyd Evans 1986). An RCB star can form dust over random spots on the stellar surface during every pulsation cycle and still appear to be a true irregular variable.

Cottrell et al. (1990) found that early in a decline the $B-V$ colors may appear redder or bluer than at maximum light. The colors vary depending on how much of the photosphere and emission regions are obscured by dust, by the optical depth of the dust, and by the relative strength of the emission lines. Sometimes very early in a decline, the colors are unchanged at first and then become bluer. This could occur if the forming cloud is smaller than the photosphere and some unreddened starlight is still visible (Cottrell et al. 1990; Feast 1990). Red declines occur if the forming cloud covers the entire photosphere.

3.2.2 *The Decline Spectrum*

Even now, extensive and simultaneous photometric and spectroscopic coverage is available for only two RCB declines, the 1967 decline of RY Sgr (Alexander et al. 1972), and the 1988 decline of R CrB (Cottrell et al. 1990). However, fragmentary data are available for more than ten declines of R CrB, RY Sgr and V854 Cen (e.g., Spite and Spite 1979; Rao et al. 1990; Lambert et al. 1990; Lawson 1992; Lawson et al. 1992; Clayton et al. 1992b; Rao and Lambert 1993a,b; Asplund 1995). However, since only three stars have been studied, little can be said about the general behavior of RCB stars. In fact, V854 Cen shows significant spectral differences from R CrB and RY Sgr during declines.

As the photospheric light is extinguished by the forming dust cloud, a rich narrow-line (~ 50 km s^{-1}) emission spectrum appears. In the visible, this spectrum consists of many lines of neutral and singly ionized metals (Payne-Gaposchkin 1963; Alexander et al. 1972). Most of the lines in this spectrum, referred to as E1 (Alexander et al. 1972), are short-lived and within two or three weeks, they have faded and are replaced by a simpler broad-line (BL) (100–200 km s^{-1}) spectrum. The narrow lines are slightly blueshifted (~ 10 km s^{-1}) from the stellar radial velocity (Spite and Spite 1979; Cottrell et al. 1990). Some of the early-decline emission lines remain strong for an extended period of time. These lines, also narrow and referred to as E2, are primarily multiplets of Sc II and Ti II. In particular, the Sc II (7) λ4246 line remains very strong. The E2 lines are primarily low excitation. There are many C I absorption lines which fill in but never go into emission (Alexander et al. 1972). This phenomena is often described as "veiling" of the photospheric absorption spectrum (e.g., Lambert et al. 1990). The Balmer lines, which are typically very weak due to the hydrogen deficiency in these stars, do not go into emission except in the case of the relatively hydrogen-rich V854 Cen. The late-decline BL spectrum is dominated by five strong lines, Ca II H and K, the Na I D lines and a line at 3888 Å which is likely to be He I (Feast 1975). This broad-line (BL) emission spectrum remains visible until the star returns to maximum light and the photospheric continuum regains dominance. In some declines, the Swan bands of C_2 are seen in emission (Payne-Gaposchkin 1963; Whitney et al. 1992; Rao and Lambert 1993b) (see Fig. 3). There are also several

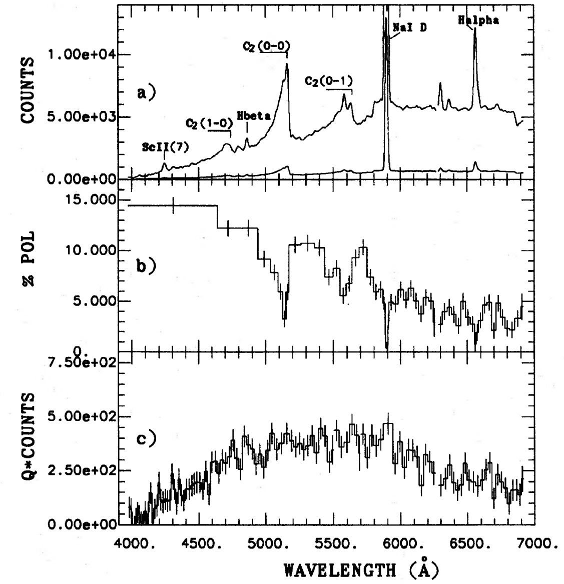

FIG. 3—The (a) spectrum, (b) polarization, and (c) polarized flux of V854 Cen during a deep decline in 1991. The continuum is highly polarized while the broad emission lines are unpolarized. (From Whitney et al., 1992; © American Astronomical Society, reproduced with permission.)

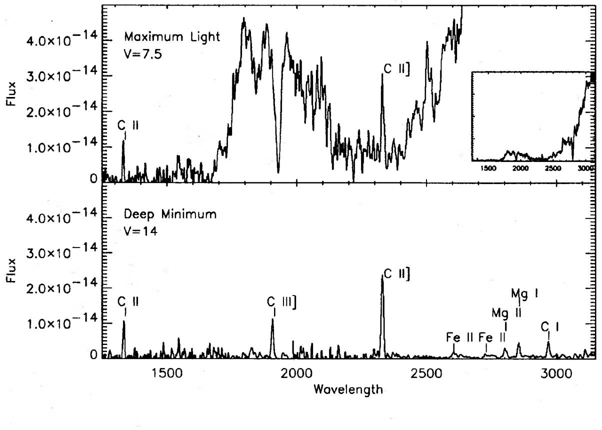

FIG. 4—*International Ultraviolet Explorer* spectra of V854 Cen. The upper panel shows a spectrum at maximum light while the lower panel shows a late decline spectrum. The inset shows the entire maximum light spectrum. Note that emission is seen even at maximum light.

unidentified features including a broad emission feature ($>$ 200 Å) lying under the Na I D lines (Whitney et al. 1992; Asplund 1995), and a number of broad features in V854 Cen. Several of these features seem to correspond to emission features seen in the Red Rectangle (Rao and Lambert 1993c).

The UV spectrum undergoes a very similar evolution (Evans et al. 1985; Holm et al. 1987; Clayton et al. 1992b) (see Fig. 4). The very early-decline UV spectrum (E1) shows blends of many emission lines which form a pseudocontinuum. The Mg II doublet is present but not yet strong. The strong apparent absorption at 2650 Å is an absence of emission similar to that seen in the solar chromosphere (Holm et al. 1987). With time, the early-decline spectrum begins to fade and be replaced by the late-decline spectrum. These spectra (E2) still show much blended emission but Mg II, Mg I λ2852, and some of the Fe II lines have become relatively stronger. The late-decline (BL) spectrum is characterized by blended emission from multiplets of Fe II (2) λ2400, Fe II (1) λ2600, Fe II (62, 63) λ2750, as well as from Mg II and Mg I. The UV decline spectra of V854 Cen are also quite different from R CrB and RY Sgr. These spectra show strong emission from C II] λ2325 and C I λ2965 which are not seen in the other stars (Clayton et al. 1992a,b; Clayton et al. 1993a).

Very little IR spectroscopic data exist. The 3–3.5 μm spectrum of R CrB is featureless (Nandy et al. 1986). Three RCB stars (R CrB, RY Sgr, V854 Cen) were observed from 8–22 μm with the Low Resolution Spectrometer (LRS) on *IRAS* (Walker 1985, 1986; Clayton et al. 1995a). Buss et al. (1993) investigated the mid-IR (5–23 μm) spectrum of R CrB. When a blackbody continuum is subtracted from these spectra, some small apparent emission features are present at 6.3, 8–9, and 11.3 μm. The low resolution and signal to noise of these spectra preclude identification of these features. Recently, Clayton et al. (1995a) re-observed R CrB, RY Sgr, and V854 Cen at 8.6 μm to look for the C_{60} feature at that wavelength. No features were found.

Very few quantitative measurements have been made of emission line strengths during declines. Herbig (1949) measured the Ca II H and K lines of R CrB during the 1948 decline and found that their strength peaked when the star had faded about 6 magnitudes below maximum. By the time the star reached minimum light at V$\sim$14 mag, the intensity of the H and K lines had dropped by a factor of 5. Holm et al. (1987) followed the C II λ1335 emission strength through the 1983 decline of R CrB and found that within the errors, the flux remained constant at the level measured at maximum light. Clayton et al. (1992b) measured the peak of the emission above the apparent continuum in spectra from the 1983 and 1988 declines of R CrB, the 1982 and 1990 declines of RY Sgr, and the 1991 decline of V854 Cen. The Mg II peak flux remains constant in R CrB even 200 days into a decline. However, in RY Sgr and V854 Cen, the emission strength decreases after about 100 days of the decline in a manner similar to that seen by Herbig in the Ca II H and K lines for R CrB in 1948. This fading of the Mg II and Ca II lines, which are part of the BL emission, indicates that the BL region can be significantly but not completely eclipsed by dust in some declines.

Emission from circumstellar gas, typically seen only during declines, is present at all times and is not necessarily part of the dust-formation process. At maximum light, the visible-light stellar continuum swamps the emission spectrum but in the UV where the stellar continuum is much fainter, emission at C II λ1335 has been detected at maximum light in R CrB, RY Sgr and V854 Cen (Holm and Wu 1982; Holm et al. 1987). This is shown in Fig. 4. Rao et al. (1981) report that emission is visible at Mg II in a very noisy high-resolution spectrum of R CrB at maximum. No emission is seen at Mg II in RY Sgr in a much higher S/N spectrum (Clayton et al. 1994). Lambert et al. (1990) have found Sc II emission filling in the core of a photospheric line in R CrB at maximum.

Spectroscopic observations at or before the beginning of a decline have found no evidence for spectral changes (e.g., Cottrell et al. 1990; Lawson 1992). However, high-velocity absorption lines have been seen in observations early in declines and again just before return to maximum light (Alexander et al. 1972; Cottrell et al. 1990; Clayton et al. 1992a, 1993a; Vanture and Wallerstein 1995). These absorption lines have velocities of about 200 km s^{-1}. Recent observations of V854 Cen at Hα and in the Na I D lines (Rao and Lambert 1993a; Clayton et al. 1993a) show very complicated emission profiles. These lines have Full Width Zero Intensities of 700–950 km s^{-1} and show high-velocity absorption components which change with time. Clayton et al. (1993a) find one component of Na I D in V854 Cen which is blueshifted by 390 km s^{-1}, a velocity 2 to 4 times that usually associated with components during declines of RCB stars. This is shown in Fig. 5. Changes in molecular bandstrengths (C_2 and CN) have been associated with declines. Payne-Gaposchkin (1963) found that the emission faded and the absorption bands were 50% stronger at minimum light than at maximum. Lambert et al. (1990), and Rao et al. (1990) also report that the absorption bands are stronger at minimum in R CrB. On the other hand, Herbig (1949) reports no significant difference between the molecular bandstrengths at maximum and minimum light. Recent long-term monitoring of R CrB shows that 50% bandstrength variations are typical of those due to pulsations occurring at maximum light (Clayton et al. 1995b). However, some of the strongest measured bandstrengths are associated with declines or suspected dust formation episodes.

Mass loss is indicated by observations of the He I λ10830 line in R CrB when it was recovering from a decline and later at maximum light. The line had a P Cygni profile extending to -240 km s^{-1} (Querci and Querci 1978; Zirin 1982). Clayton et al. (1994) find similar structure in the Mg II λ2800 lines for RY Sgr and R CrB. In both components of Mg II, there is an absorption from about -100 to -200 km s^{-1}. This corresponds well to the blueshifted absorptions seen at times in RCB stars. These features may be associated with gas being dragged along with the dust as it is blown away from the star by radiation pressure or perhaps by a stellar wind.

Extinction curves finally confirmed the suggestion of

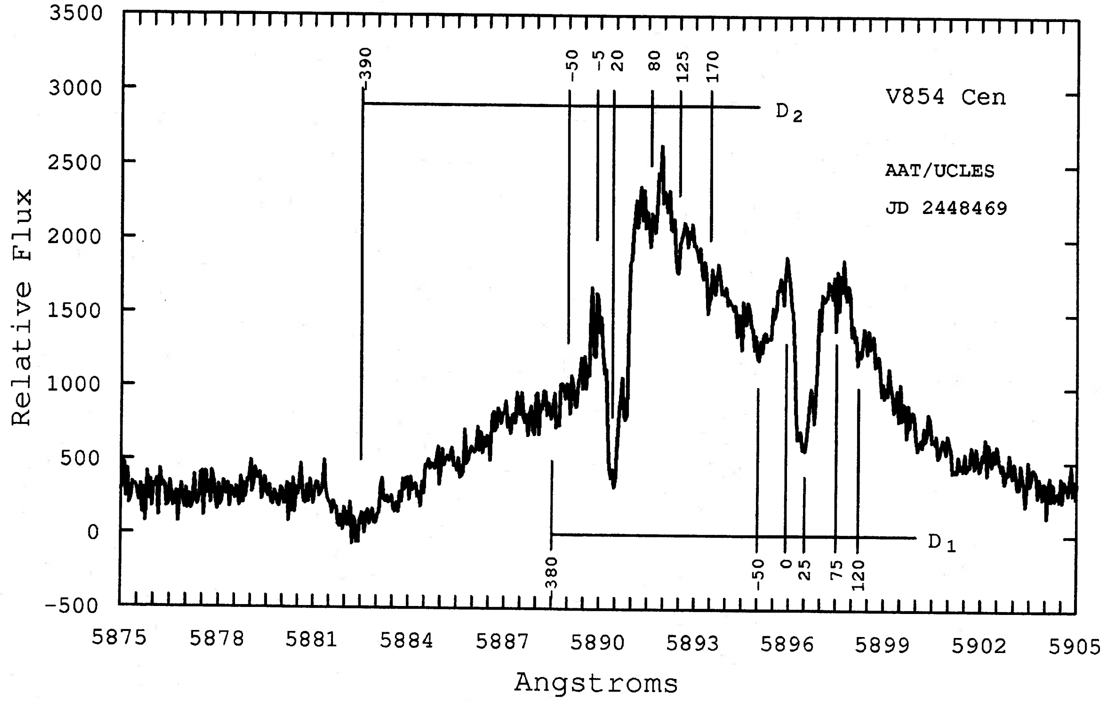

FIG. 5—Na I D line emission in V854 Cen during a decline. Possible identifications of blue- and redshifted absorption components are marked. The velocities indicated are with respect to the stellar rest frame. (From Clayton et al., 1993a; © Royal Astronomical Society, reproduced with permission.)

O'Keefe (1939) that the dust causing the declines in RCB stars is carbon rich. The UV extinction curve for RY Sgr has a peak in the 2400–2500 Å range which can be fit well by amorphous carbon dust (Holm et al. 1982; Hecht et al. 1984; Wright 1989; Hecht 1991). Since then several studies have confirmed and extended this result. Hecht et al. (1984) found that the extinction curves for dust measured during minima of R CrB and RY Sgr are consistent with extinction from glassy or amorphous carbon grains with a size distribution of 0.005–0.06 μm. Similar extinction curves have been found for RY Sgr (Clayton et al. 1992b), R CrB (Holm et al. 1987; Holm and Doherty 1988), V348 Sgr (Drilling and Schönberner 1989; Drilling et al. 1996) and MV Sgr (Evans et al. 1985). Jeffery (1995) considered the UV extinction properties of other carbon materials such as fullerenes.

3.2.3 *Infrared Emission*

Near-IR photometry of RCB stars has produced two interesting results (Feast et al. 1977; Feast 1979, 1990). First, during a decline, while the *V*-band (photospheric) brightness is plummeting, the *L*-band brightness which is dominated by dust emission shows no significant increase or decrease, and continues to mirror the pulsational variations of the photosphere (Feast 1979) (see Fig. 6). This implies that only a small amount of dust is produced in any one decline and that it does not form in a complete shell around the star. Rather the dust apparently forms only over a small solid angle of the stellar surface (Forrest et al. 1971; Feast 1986). Second, large long-term brightness variations in the near-IR are seen in RCB stars (Forrest et al. 1971; Strecker 1975; Glass 1978).

years, show semi-periodic variations of 1–2 magnitudes with characteristic periods of one to several thousand days (Menzies 1986; Feast 1990). The simplest explanation for these variations is that the amount of dust produced by RCB stars varies greatly on time scales of a few years. An increase of 2 magnitudes in IR luminosity indicates that the amount of warm dust may have increased by 6 or more times. The amount of IR re-radiation is significant ranging from roughly 10% to 50% of the total radiation (Humphreys and Ney 1974). Therefore, one would expect some kind of correlation between IR brightness and decline activity. If dust is ejected randomly, then the correlation might be quite weak as declines occur during some episodes of active dust formation, as measured by IR brightness, and not others. Observations covering about 19 years for RY Sgr and about 11 years for R CrB have been published (Menzies 1986; Feast 1986, 1990). In this dataset, there is no obvious correlation between the IR brightness and frequency of declines. For example, Menzies (1986) predicted a decline of RY Sgr for 1986 based on an increase in its IR brightness. RY Sgr did not decline until 1990. However, UW Centauri was IR bright during two decline phases and faint during two lengthy periods at maximum light (Feast 1990). Glass et al. (1994) find similar long-term variations in two of the LMC RCB stars and found a possible correlation between the IR brightness and decline activity for W Men. If the visible and IR behavior are not correlated then there is a large amount of dust being produced around the star but not along the line of sight. This might occur if dust is ejected preferentially at the equator or the poles. One RCB star, Y Muscae, has not experienced any

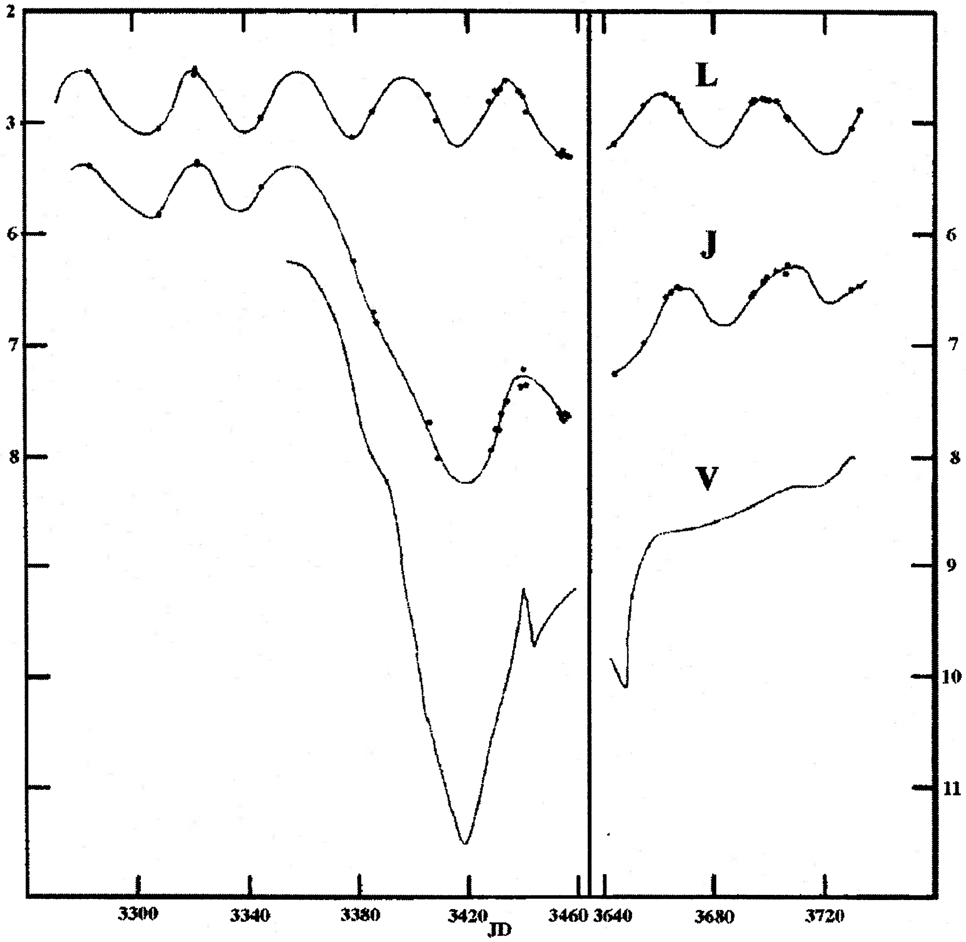

FIG. 6—*V*-band (lower curve), *J*-band (middle curve) and *L*-band (upper curve) photometry through a decline of RY Sgr. The *V* band is mostly stellar flux while the emission in the *L* band is primarily due to circumstellar dust. (From Feast, 1979; © Univ. of Waikato, reproduced with permission.)

a hot dust shell similar to those seen in other active RCB stars (Walker 1986; Milone 1990). Therefore, Y Mus is regularly producing dust but rarely along the line of sight towards us.

Ground-based and *IRAS* photometry indicate that dust around RCB stars has a temperature range of ~650–900 K (Kilkenny and Whittet 1984; Walker 1986). The *IRAS* data for 16 RCB stars have been re-examined (Walker 1994). Four stars (R CrB, RY Sgr, V CrA, and UW Cen) show evidence of resolved fossil dust shells. The largest is the R CrB shell which is 20′ in diameter. This corresponds to about a parsec at the assumed distance of R CrB (Rao and Nandy 1986). This shell, which was formed from 10^4 to 10^5 years ago, is not related to the present mass loss (Gillett et al. 1986). An unsuccessful search was recently made in the fossil shell for H I emission at 21 cm (Clayton 1996, unpublished data). V348 Sgr and UW Cen have resolved dust shells seen in reflected starlight (Pollacco et al. 1990; Pollacco et al. 1991). The UW Cen shell is quite asymmetrical and possibly shows two sets of diagonally opposed jets centered on the star.

3.2.4 Polarization

Starlight becomes polarized when it scatters off circumstellar gas and dust. This polarized component becomes relatively more important during RCB declines when direct unpolarized starlight is obscured by dust along the line of sight. Large polarizations have been measured in several declines (Serkowski and Kruszewski 1969; Coyne and Shawl 1973; Stanford et al. 1988; Efimov 1990; Whitney et al. 1992). Coyne and Shawl found large polarization variations associated with a brightness minimum of R CrB in 1972. During a decline of 7 magnitudes, the polarization rose from 0.29% to 3.29% in the *B* band over 3 weeks. Whitney et al. (1992) observed V854 Cen during a deep decline ($\Delta m = 8.2$) and found a very high continuum polarization, ranging from 14% at 4200 Å to about 4% at 6500 Å . The broad emission lines were unpolarized, so this emission is seen directly and not scattered by dust (see Fig. 3). Feast (1986) and Fadeyev (1988) argue that the emission present in deep declines is not associated with a static "chromosphere," but with other clouds previously ejected. The unpolarized emission lines suggest a picture of an emission region separate from the clouds. However, if the emitting gas were mixed in with the dust clouds it would likely have less polarization than the continuum flux which is scattered photospheric radiation, so emission from the dust clouds is not completely ruled out by these observations. In such a deep minimum, the visible continuum flux is almost entirely scattered light, resulting in its high polarization. The scattered flux may arise in the same clouds contributing to the observed IR flux if the albedo is low and the grains forward throwing (Whitney et al. 1992). The blue part of the spectrum is probably all scattered light since the polarization is so high ($Pp \sim 14\%$) and the star so faint. The decrease to longer wavelengths could be due to dilution by unscattered flux, since the optical depth would be smaller. Or it could be caused by scattering from dust grains which have a particular size distribution. The wavelength dependence is similar to that seen by Coyne and Shawl which was a good fit to scattering from 0.05 μm graphite particles. They found that the wavelength dependence varied with time during a decline in R CrB. They suggested that this was due to evolution of the dust grain size distribution. Hecht et al. (1984) suggest that evolution of the dust grains takes place soon after they are formed, stopping by the time the cloud begins to disperse.

Stanford et al. (1988) found evidence from polarization observations of three declines that there may be a preferred plane for the dust ejections in R CrB. Clayton et al. (1995b) using data from two additional declines of R CrB find that the evidence for a preferred plane is less compelling. During declines, the fraction of flux scattered from dust around the star seems to be relatively constant at $\sim 10^{-3}$ to $10^{-4} F_*$ (Whitney et al. 1992; Clayton et al. 1995b). Outside of declines, there is evidence in R CrB for significant variations at a level of 0.1%. A polarization of about 0.1% would be expected due to scattering from an optically thick blob with a diameter of 20°–30° as seen from the star (Code and Whitney 1995).

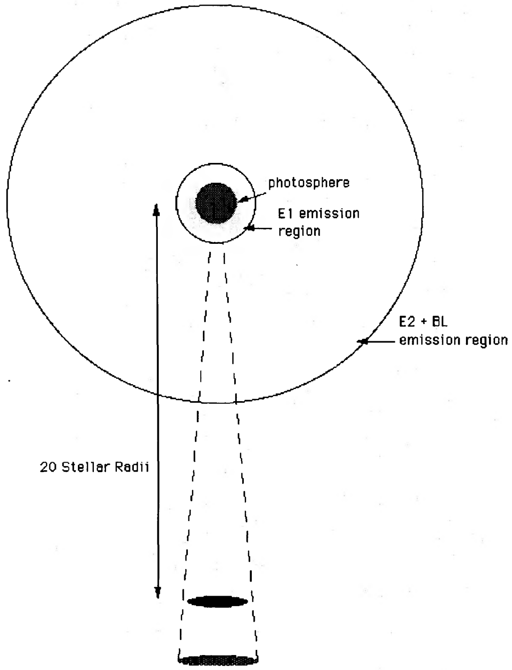

FIG. 7—Scenario for 20 R_* dust formation. In this scenario, dust forms at a distance of $\sim 20\ R_*$ when the gas reaches the condensation temperature of carbon. The cloud then moves away due to radiation pressure, expanding to cover the photosphere and parts of the emission regions.

4. UNDERSTANDING RCB STARS

Before considering models of RCB stars in detail, here is a summary of the observational data described above:

- Most RCB stars are F or G supergiants with $T_{eff} = 5000$–7000 K.
- Hydrogen is extremely under-abundant, carbon and nitrogen are over-abundant.
- RCB's are single stars.
- RCB star declines occur at irregular intervals.
- All RCB stars show small semi-regular brightness variations which may be due to pulsations.
- A correlation is seen between pulsational phase and decline onset for RY Sgr and V854 Cen but not for R CrB.
- No spectroscopic changes are seen before decline onset.
- High-velocity blueshifted absorptions are seen up to -390 km s^{-1} in Hα and Na I D lines during declines.
- He I, Mg II show blueshifted absorptions.
- E1+ E2 emission is blueshifted $\sim$ 10 km s^{-1}.
- BL emission has FWHM of 200 km s^{-1}
- At decline onset, colors may become bluer or redder than at maximum light.
- Initial decline is 3–6 mag in about 50 days.
- Fast or slow recoveries and/or multiple declines follow. Final recovery may be slow.
- E1 emission fades in 10–30 days.
- E2 emission fades in 50–150 days.
- BL emission fades but never disappears.
- E1, E2, and BL emission lines appear in every decline.
- E1 emission consists of singly ionized and neutral metals.
- E2 emission is primarily multiplets of Sc II and Ti II.
- The BL spectrum in the visible is dominated by Ca II H and K, the Na I D lines and He I λ3888.
- Some emission lines are always present even at maximum light.
- BL emission lines are unpolarized.
- IR emission from dust does not vary during declines.
- IR emission from dust shows large variations on a time scale of years.
- IR brightness and decline frequency may not be well correlated.
- Polarimetry implies the fraction of scattered light is 10^{-3}–$10^{-4} F_*$.
- Several RCB stars have large fossil dust shells.
- Dust is amorphous carbon

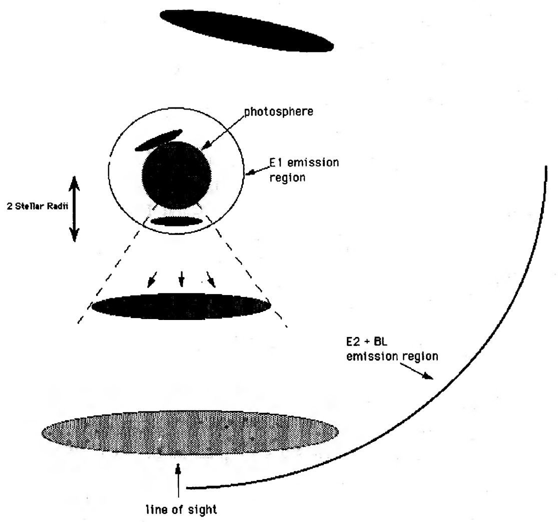

FIG. 8—Scenario for Near-Star dust formation. In this scenario, dust forms near the star and moves quickly away due to radiation pressure, expanding to cover the photosphere and parts of the emission regions. Small dust clouds may form during each pulsation cycle of the star. Declines only occur when a cloud forms along the line of sight.

4.1 Dust Formation

To cause a decline, dust must either form along or pass into the line of sight to an RCB star but polarimetry and IR photometry both indicate that dust is generally present around the star even when there is none between us and the star. Clouds of dust orbiting an RCB star have been proposed to account for these observations but this model has difficulty fitting the observational data (Forrest et al. 1972; Wing et al. 1972; Hartmann and Apruzese 1976). The passage of a dust cloud across the star is not consistent with the structure of the decline light curve nor with the evidence for grain evolution (Hecht et al. 1984). So dust ejection from a secondary star in a binary system must be invoked to make this model viable. However, there is no evidence of binarity in RCB stars.

A second, more likely model involves dust forming from material lost from the RCB star itself (see Figs. 7 and 8). This model has a long history (Loreta 1934; O'Keefe 1939). A simple ejection model has been developed assuming homogeneous nucleation of carbon dust in thermodynamic equilibrium (Fadeyev 1986, 1988; Feast 1986). In this model, shown in Fig. 7, mass is lost and moves away from the star until it reaches the condensation temperature of carbon dust ($\sim$1500 K) at $\geqslant 20\ R_{\ast}$. The dust cloud is large enough to eclipse the photosphere of the star as seen from Earth, subtending a cone angle at the star of perhaps 20° to 40°. The dust, once formed, blows away from the star by radiation pressure, eventually dissipating and allowing the stellar photosphere to reappear. The dust forms locally in a patch or puff not as a complete shell. At any given time, there may be a number of puffs arranged around the star. As the photosphere is eclipsed by the expanding cloud, an emission spectrum is revealed, which is produced by gas dragged along with the dust moving away from the star. Most of the emission lines quickly fade as the gas is eclipsed in turn.

While simple, the $20\ R_{\ast}$ condensation model has severe problems. As pointed out by Fadeyev (1988), the most serious is the relationship between pulsation phase and decline onset which is seen in at least two RCB stars. If real, this correlation implies a physical connection between the stellar atmosphere and the location of dust formation. This is hard to imagine for dust forming at $20\ R_{\ast}$. Then, there is the question of how mass is lost from the stars and moved to the condensation point. There is some evidence from He I λ10830 and Mg II λ2800 for something like a stellar wind (Feast 1990; Clayton et al. 1994). The most compelling evidence against the $20\ R_{\ast}$ dust formation scenario is in the structure of the RCB decline light curve. The time scales for the rise and fall in the brightness of the star, and the appearance and disappearance of the emission lines give information on the sizes of the forming cloud and the emission line regions, and the acceleration and dispersal times of the dust (Clayton et al. 1992b; Whitney et al. 1993; Goeres 1996). We know that the E1 emission appears in every decline so there is a maximum size to the forming dust cloud. Using the standard assumptions for the forming dust at $20\ R_{\star}$, the timing of the E1 fading implies that the cloud always forms at $\sim$ 90% but never more than 100% of the size of the E1 region before expanding to cover it. Finally, typical declines are characterized by both fast and slow recoveries to maximum light. Dust formed at $20\ R_{\star}$ cannot explain the fast recovery times because the dissipation time is too long.

Many of these problems disappear if we assume that dust forms near the photosphere ($\sim 2R_{\ast}$) and blows away from the star by radiation pressure. This model is shown in Fig. 8. This was originally suggested by Payne-Gaposchkin (1963) who proposed that the dust formed in the upper atmosphere of the star under the "chromosphere." Dust forming near the star naturally forms a cloud with a maximum extent about the size of the star. If the cloud is forming from material at a large distance from the star, there is no *a priori* constraint on the cloud size. Dust forming near the star feels a radiation force several hundred times greater than at $20\ R_{\star}$ and will accelerate quickly away from the star, so there is no need for a separate mass loss mechanism. This can easily account for the $\sim$200 km s^{-1} velocities seen in the blueshifted absorption features. Assuming the grains move away radially due to radiation pressure, then the time scale for cloud dissipation can be used to calculate the absolute distance of the dust (Pugach 1990; Whitney et al. 1993). These calculations find that typically the dust cloud is at a distance of about $10\ R_{\star}$ at 50 days into a decline in agreement with the near-star scenario. This model can easily explain both fast and slow recovery times in the light curve. However, for a prolonged decline, successive dust formation episodes are required. The main drawback of the near-star model is the dust condensation temperature. Assuming thermodynamic equilibrium, it is much too hot to form dust. However, the conditions near the star are far from thermodynamic equilibrium allowing the possibility of dust formation.

Carbon nucleation in RCB stars may differ in some respects from that occurring in the outflows of mass-losing red giants (Goeres and Sedlmayr 1992; Whitney et al. 1993; Clayton et al. 1995a). First, in RCB stars the nucleation will proceed in the presence of much smaller amounts of hydrogen than in red-giants where the hydrogen abundances are normal (Lambert 1986). Second, a few percent condensable carbon is present in RCB stars, two orders of magnitude greater than in red-giants. Finally, the condensation temperature of carbon in the absence of hydrogen is considerably higher than it is in the presence of hydrocarbons (Donn 1967).

Shocks have been detected in the atmosphere of one RCB star, RY Sgr. If RCB stars have shocks propagating through their outer atmospheres, they will cause local density enhancements, and encourage nonequilibrium conditions. The carbon chemistry under these conditions has been described by Goeres and Sedlmayr (1992) and Woitke et al. (1995). During the passage of a shock, a fluid element is first heated and compressed, then re-expands, cooling adiabatically. When the effects of non-LTE radiative heating and cooling via free-free, bound-free, and line transitions (both atoms and molecules) are taken into account, the preconditions for carbon nucleation may be temporarily present. The chemistry of an RCB star envelope is completely dominated by a gas of pure carbon embedded in a background of inert helium (Goeres and Sedlmayr 1992). As soon as polar molecules become abundant in the gas, they begin to dominate radiative heating and cooling. Carbon monoxide (CO) plays an overwhelming role since it is the most abundant polar molecule by two orders of magnitude (Woitke et al. 1995). CO formation can begin at temperatures as high as 5000 K. The CO cools very efficiently and temperatures in the CO clouds may drop to below 2000 K (Ayres 1981; Woitke et al. 1995). Dust then forms from carbon chains and clusters. Once formed in optically thick clouds, the dust can be self-shielding. Such conditions present locally over the surface of the star could form a "puff" of carbon dust which then is ejected by radiation pressure. The observed time scales for RCB dust formation fit in well with those calculated by the carbon chemistry model (Feast 1986; Woitke et al. 1995). These conditions for dust formation could be improved if the puffs form over giant convection cells in the RCB star atmosphere (Wdowiak 1975). The linchpin of the carbon chemistry scenario is the CO, yet there is no published detection for an RCB star. Unsuccessful searches at various wavelengths have been made for CO in several RCB stars including R CrB and RY Sgr (Wilson et al. 1973; Munch et al. 1973; Zuckerman et al. 1978; Knapp et al. 1982; Lambert 1986; Zuckerman & Dyck 1986; Wannier et al. 1990; Rao et al. 1991). However, Z UMi is reported to show strong CO bands (Rao 1995, personal communication).

Feast (1990, 1996) has updated the 20 R_* condensation model and attempted to deal with some of its weaknesses. He suggests that the mass loss is a slow Eddington-driven outflow of material. Asplund and Gustafsson (1996) suggest that RCB stars may be super-Eddington. The emission lines do show a blueshift of about 10 km s^{-1}. In this model, the gas forms a shell at $\geqslant 20\ R_*$. When the density of the shell becomes high enough, dust condenses (Feast 1990). Alternatively, the dust forms in instabilities in the flow (Feast 1996). This is similar to the nonequilibrium model outlined above. A recent model of dust formation in a flow in carbon stars is contained in Egan and Leung (1995). Once formed, dust blows away through radiation pressure. In this model, the IR flux and frequency of declines should be well correlated. The IR flux and the number of declines should first rise as the dust forms in the shell and then fall as the dust disperses until the shell refills with gas and a new cycle begins. Finally, Feast (1996) offers several alternative mechanisms to account for fast recoveries in the decline light curve in the 20 R_* condensation model. He favors stellar flux scattered by electrons in the outer uneclipsed portion of the stellar atmosphere. This is unlikely since we know from polarization studies that the fraction of stellar light scattered (by electrons or dust) towards us seems rather constant at about $10^{-3}F_*$ (Clayton et al. 1995b). So small increases in the brightness of the star due to pulsations cannot account for fast recoveries of several magnitudes unless pulsations or changes in atmospheric structure allow a fair fraction of the photosphere to appear above the edge of the eclipsing cloud. The mass loss rates from both the 2 and 20 R_* models are about 10^{-6}–$10^{-7} M_\odot \mathrm{yr}^{-1}$ assuming 5 to 10 puffs per year (Feast 1986; Clayton et al. 1992b).

4.2 Emission Lines

The nature of the emission-line region or regions is not well understood. This emission, often described as "chromospheric," does not look anything like chromospheric emission in other stars. The observational evidence indicates that emission lines are always present and there is no evidence for variations related to shock heating such as is seen in Miras (Brugel et al. 1986; Clayton et al. 1994). The small blueshift of the narrow emission lines suggests that they could be part of the proposed super-Eddington flow but not the much faster ($\sim$200 km s^{-1}) expansion of the dust clouds. The observed width of the broad emission lines and their blueshifted absorptions are consistent with the dust-cloud velocities. However, the BL emitting region may be kinematically similar to the E1+E2 regions if the lines are broadened due to high optical depths in the BL lines. Clayton et al. (1992a) found large emission measures for the UV BL lines. If n_e is about 10^9 cm^{-3} then the implied high optical depth may result in significant broadening of the BL lines. These broad emission lines are unpolarized so they are either occupy a separate volume from the dust clouds or are mixed with the dust so that the geometry produces no net polarization.

The fading of the emission lines during declines makes sense if the star is surrounded by three somewhat distinct emission regions responsible for the E1, E2, and BL emission, with the E1 emitting region having the smallest radius, followed by the E2 emitting region, and then the BL region. The E1+E2 emission has always been considered separate from the BL emission because of the large difference in line widths. Based on the conclusion of dust formation near the star and the assumptions of Sec. 4.1, the E1 region is calculated to have a radius of about 1.5–2 $R_\star$. The E2 region is about 5 times as large and the BL region somewhat larger still.

Clayton et al. (1992a) find the emission measure loci of Mg II, Si II, and C II] are consistent only for electron densities near 2×10^{10} cm^{-3} and the emitting regions might have characteristic electron temperatures near 6000 K. These temperatures are typical of the line-forming regions of red giants (Judge 1986). Also, the presence of C II λ1335 and C III] λ1909 and the He I lines indicates that a higher temperature emitting region must exist. The He I λ10830 absorption line is a pure indicator of a hot atmospheric region, usually the base of a transition region between the chromosphere and corona, with no photospheric contamination to its profile in stars cooler than B2. This behavior in R CrB is highly unusual for a star in this part of the H-R diagram, as there is little in the visible spectra to suggest the existence of a dynamic upper atmosphere. Based on the He I emission, Surendiranath et al. (1986) calculate T$\sim10^4$ K and $n_e\sim10^{11}-10^{12}$ cm^{-3} assuming a highly excited, electron-collision dominated gas moving at high velocity. Feast (1996) suggests that the He I is collisionally excited in a high-velocity flow.

4.3 Stellar Evolution

The evolutionary history of RCB stars remains mysterious. Clues can be found in the stars' spatial distribution and radial velocities, their abundances, pulsations, lack of binarity and circumstellar shells. Since RCB stars are so rare, they must be either a unusual occurrence or a fast evolving stage in the life of a star. Based on this, Schönberner (1986) estimates a lifetime of 3×10^4 yr for RCB stars. The RCB, HdC and EHe stars all have similar abundances indicating that they may be related objects (Lambert and Rao 1994). Model atmospheres using the abundance data of Cottrell and Lambert (1982), and Schönberner (1975) indicate that $T_{eff}\sim6900$ K and $\log g=0.45$ to 0.65. When these values are compared to the results of Schönberner's (1977) time-dependent evolutionary tracks, they fall near 0.7 $M_\odot$. These models imply a connection between the RCB stars and the hotter EHe stars. A cool RCB star will evolve to an EHe star in about 5000 yr (Schönberner 1986). Previously, this result was supported by the observed period decrease in RY Sgr which implied a pulsational lifetime of about 3000 yr. However, Lombard and Koen (1993) have argued that the RY Sgr period variations are random, leaving the question of whether there are systematic period variations wide open. Models of linear nonadiabatic radial pulsations in RCB stars imply masses of about 0.8 $M_\odot$ (Saio and Wheeler 1985; Saio 1986, Weiss 1987). If the hydrogen-deficient stars are single stars of Population II then these low-mass helium stars must come from a low-mass precursor (Schönberner 1986).

Two major evolutionary models have been suggested for the origin of RCB stars, the Double Degenerate (DD) and the Final Helium Shell Flash (FF) conjectures (Schönberner 1986; Renzini 1990). Both involve expanding white dwarfs to the supergiant sizes assumed for RCB stars. The former model involves the merger of two white dwarfs and the latter model involves the expansion of a white dwarf to supergiant size by a final helium shell flash (Iben et al. 1983; Renzini 1990). A third model suggests that RCB stars are binaries in the second common envelope phase with a low mass companion orbiting inside the envelope (Whitney et al. 1991). The DD and FF scenarios both require RCB stars to be an older population of stars, which is supported somewhat by the spatial distribution and radial velocity data (Drilling 1986). The common envelope model may require a younger stellar population (Lambert and Rao 1994). Great uncertainty remains as to whether either or both of the FF and DD models can account for the RCB stars. To get the full flavor of the arguments for and against these models, I suggest reading Schönberner (1986), Renzini (1990), and Lambert and Rao (1994). These reviews stress that detailed modeling of neither the DD nor the FF model has been attempted and is desperately needed. As a motivation, Schönberner (1986) and Renzini (1990) list two constraints on any RCB model:

(1) The end result is an evolved, single, low-mass star belonging to an old population
(2) Surface abundances are a mix of original, CN-processed and 3-α processed material. To this Lambert and Rao (1994) add:

(1) Li production must be possible.
(2) The models must account for the Fe-poor RCB stars.

Webbink (1984) proposed a model where RCB stars evolve from a population II binary that has reached the white-dwarf stage (see also Iben and Tutukov 1985). According to this scenario, RCB stars form from a He-CO white-dwarf (WD) binary system in which the stars coalesce through loss of angular momentum from gravitational wave radiation. These close white-dwarf binaries result from an intermediate-mass binary system with two phases of mass exchange, the second one in a common envelope. As the two WD's approach one another, the 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 helium-burning shell in the center of a ~100 $R_\odot$ hydrogen-deficient envelope, is believed to be that of an RCB star. The main problem for this model is whether there are enough CO-He WD binaries which are orbiting closely enough to coalesce in less than a Hubble time. Renzini (1990) reports the results of a small survey of WD binaries which suggests there are not enough such binary systems. If RCB stars are old disk/Pop I stars (see Sec. 2) then they can be quite old yet not very metal poor. This model can possibly produce the right surface abundances of H, C, and N although producing Li is a problem (Schönberner 1986). In addition, the implied lifetimes seem more than adequate.

About 10% of post-AGB stars are predicted to undergo a final helium flash. A convective shell generated by the FF consumes the remaining hydrogen on the surface and the star inflates in size (Renzini 1990). The surface hydrogen is rapidly mixed in toward the higher temperature layers. This mixing causes the helium convective shell to split in two, with hydrogen and helium burning in the upper and lower shells, respectively. The energy released leads to an expansion of the upper shell. Schönberner (1986) rejects this model immediately because of its very short predicted lifetimes of about 10^2 yr but Renzini (1990) argues that the lifetime is longer if the mass is low enough. Renzini also argues that the right abundances including Li can be produced although getting a correct C^{13}/C^{12} ratio is difficult. Neither the FF nor DD models can account for the peculiar RCB stars with their low Fe abundance (Lambert and Rao 1994). This may result from unusual nucleosynthesis in the atmospheres of these stars or separation of the condensable elements from the atmosphere through dust formation (Lambert and Rao 1994). The latter has been proposed for post-AGB stars which are metal poor (Mathis and Lamers 1992; Bond 1992). In the case of stars which have normal abundances, both Si and Fe will be lost as Si forms silicates. But in RCB stars, the overabundance of carbon means that all the oxygen is in CO and so not available to condense into silicates. Therefore, Fe may be preferentially lost, if iron grains are formed, creating the large observed Si/Fe ratios. It should be noted that the C/He ratio in RCB stars is assumed so the amount of metals is not directly measured (Lambert and Rao 1994).

In the FF model, there is a close relationship between RCB stars and planetary nebulae (PN) as both are in the post-AGB phase while in the DD model there should be no such relationship (Renzini 1990). Therefore, the fraction of RCB stars associated with PN could help distinguish between the two evolutionary models. The FF can occur up to 10^5 yr after the PN ejection so these envelopes may be difficult to detect (Renzini 1990). Schaefer (1986) attempted such a survey using the spectral index of *IRAS* data for RCB stars. Only 3 FF candidates were found, none of which is definitely an RCB star. One is V605 Aql which recently showed RCB behavior and is the central star of a PN (van den Bergh 1971; Bond et al. 1993). There is a large fossil dust shell around R CrB and other RCB stars. V348 Sgr and UW Cen show visible dust nebulosities. In addition, two PN, A30 and A78, have hydrogen-deficient knots of nebulosity and central stars with WR-like spectra. Renzini (1990) suggests that these PN were RCB stars about 2000 years ago.

5. FUTURE DIRECTIONS

It is a terrible cliché to say that more observations are needed but more observations are needed. In particular, long-term spectroscopic, photometric and polarimetric monitoring are needed along with detailed models to attempt to find answers to some of these questions:

- Can dust form near the star?
- Are declines really correlated with pulsation phase? Then does dust form randomly somewhere over the surface of the star each pulsation cycle?
- Do all RCB stars pulsate?
- Is there a systematic variation (increase or decrease) in the pulsation periods related to the star's evolution in the HR diagram?
- What causes dust formation activity of RCB's to change on time scales of a few years?
- All models of dust formation in RCB stars involve condensation of circumstellar gas into dust yet observers have looked in vain for a spectroscopic signature of the condensing gas. So where is the CO?
- Y Mus and V854 Cen are both active RCB stars as seen in the IR but one has frequent declines and the other very few. Is this telling us something fundamental about RCB stars or is it just small number statistics?
- What is the evolutionary status of the RCB stars? "Back of the envelope" calculations have shown that the Final Flash and Double Degenerate models are promising and have potentially fatal weaknesses. Detailed modeling is needed to determine whether one or both may in fact produce RCB stars.

This research made use of the SIMBAD database, operated by CDS in Strasbourg, France. Much of this work would not have been possible without the tireless work of Janet Mattei and the AAVSO in monitoring the RCB stars. I would like to thank my many collaborators during my work on RCB stars. In particular, I would like to thank Barb Whitney and Warrick Lawson. I would also like to express my appreciation to William Bidelman, Howard Bond, Peter Cottrell, John Drilling, Michael Feast, Dave Kilkenny, Dave Lambert, Warrick Lawson, Janet Mattei, Kameswara Rao and Barb Whitney for reading and commenting on this manuscript.

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