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High-resolution spectroscopy of R CrB – pulsations, shells and mass loss

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ABSTRACT

High spectral resolution observations obtained in 1994 and spanning three pulsation cycles of R CrB are discussed along with available *UBV* photometric observations for the same epochs. Model atmosphere based analyses of the spectra at pulsation light maximum and minimum show the atmosphere to be cooler by 500 K at minimum. Radial velocities of high- and low-excitation lines at maximum light show, on one occasion, a marked velocity difference. Weak blueshifted Hα emission is seen in spectra at the phase of minimum light. In addition to a photospheric component, the Na I D lines show absorption components from circumstellar gas. One strong component not seen in 1990 or early 1993 may be a result of gas ejected during the late-1933 deep decline.

Key words: stars: atmospheres – circumstellar matter – stars: individual: R CrB – stars: mass-loss – stars: oscillations – stars: variables: other.

1 INTRODUCTION

The R Coronae Borealis stars (RCBs)[1] are yellow supergiants with two particularly distinctive traits: a hydrogen-deficient atmosphere and a proneness to fade at unpredictable times. Happily, the eponym is bright and, when not in deep decline, readily studied spectroscopically with small to moderate sized telescopes. Photometric variations of R CrB have been well observed. At maximum light, there is a semiregular variation with leading periods of 47 and 53 d and an amplitude of $\lesssim$0.1 mag in *V* (Fernie & Lawson 1993; Fernie 1989, 1991). The variation is generally attributed to an atmospheric pulsation but if the atmosphere of an RCB star consists of a small number of giant convective cells, variations in the number of cells could produce light variations probably with a period of approximately a month (Feast 1996). Spectroscopic scrutiny of the variations has not been reported although radial velocity variations have been reported (Raveendran, Ashoka & Rao 1986; Fernie & Lawson 1993). This paper describes our initial high-resolution survey of the spectral variability of R CrB when not in a deep decline.

About 50 years ago, the spectacular declines of light were attributed to circumstellar carbon-rich dust formation (Loreta 1934; O'Keefe 1939). It is still not clear how and where the dust condensation occurs in the circumstellar environment. It has been suggested that stellar pulsations might trigger or assist dust formation and influence subsequent ejection of a cloud shrouding the photosphere – see Lawson, Cottrell & Clark (1992) for a discussion of RY Sgr, an RCB with a well-defined pulsation. There are strong arguments suggesting that dust formation occurs in 'clouds' or 'puffs' and is not a spherically symmetric happening (see Feast 1986). Location of the initial site of dust formation is more controversial. Simple estimates of thermal balance suggest that the low temperatures required for dust formation occur only at great distances from the warm ($T = 7000$ K) photospheres of the RCBs like R CrB and RY Sgr: $R/R_* = 20$ (Fadayev 1986). On the other hand there is observational evidence, especially as marshalled by Clayton, Whitney & Mattei (1993), Clayton (1996) and Woitke, Goeres & Sedlmayr (1996) suggesting that dust condenses much closer to the star. If the latter view is correct, one would expect there to be a coupling between pulsation of the atmosphere and the onset of a decline caused by dust formation. This coupling may be explored best through spectroscopic monitoring.

Our interest in R CrB was renewed in 1994 March when a high-resolution spectrum of the Na D lines showed strong

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[1]RCB denotes a star of the R Coronae Borealis type. R CrB is used exclusively to refer to the eponym.

blueshifted components that had not been present in 1990 May (Lambert, Rao & Giridhar 1990). We discuss here spectra obtained until the end of 1994 July.

2 OBSERVATIONS

The observations were with one exception obtained at the W. J. McDonald Observatory using either the Sandiford Echelle spectrometer (McCarthy et al. 1993) on the 2.1-m reflector or the Tull (1972) coudé spectrometer at the 2.7-m reflector. The Sandiford spectra have a resolving power of 60 000 and the coudé spectra (which were used to obtain the Na I D lines) have a resolving power of 120 000. The Sandiford spectra cover several hundred Ångströms. A blue spectrum obtained in 1993 April with the 1.2-m coudé feed at Kitt Peak by Vincent Woolf and Jos Tomkin at a resolving power of 72 000 covers the region 4000 to 4400 Å with some gaps. All spectra were wavelength calibrated using spectra of the Th–Ar hollow cathode lamp taken just before and after the stellar exposure. A check with the terrestrial water vapour lines in the region of Na I D show that the fit is accurate to 0.3 km s^{-1}. Available observations are summarized in Table 1. Photometric information listed in Table 1 is taken from APT campaigns and kindly provided by Don Fernie. The radial velocities of some representative lines are also listed. Radial velocities mentioned in the text and table are all heliocentric. These spectra have been supplemented with the spectra obtained in 1990 (discussed in Lambert et al. 1990). Reduction of these CCD spectra have been done both at Bangalore and Austin using the IRAF package.

The light and colour curves during the time of our observations are shown in Fig. 1 where we have used observations provided by Fernie & Seager (1994) and Fernie (1995, private communication) for the interval from early 1993 to mid 1994 and including the decline that began in 1993 September. Arrows on Fig. 1 denote the dates of our spectroscopic observations. Our sequence of spectroscopic observations began in 1994 March (near MJD = 9400) just after the return to maximum light from the decline in late 1993 (MJD ≃ 9220 to 9380). A semiregular variation in V, $B-V$ and $U-B$ is quite evident. Fernie & Seager (1994) showed that the dominant period was 37.5 ± 1.0 d in 1992 and 36.7 ± 0.9 d in 1993 (a mean period of 35.52 d might satisfy the epochs of maximum light in both years). The light curve over the period of our observations shows successive minima separated by about 55 and 40 d whereas the maxima are separated by 54, 46 and 39 d. The trend may indicate the period relaxing to the 1992–93 values following the 1993 light decline.

3 DESCRIPTION OF THE SPECTRUM AT MAXIMUM AND MINIMUM

The spectrum of 1994 April 2 (MJD = 9445) was obtained close to light maximum and bluest colour (smallest $B-V$ value). The spectra obtained on 1994 April 29 and May 1 (MJD ≃ 9473) correspond to light minimum and reddest colour. These spectra have been analysed in detail as representative of maximum and minimum light. In addition the spectra of 1994 June 24 to 27 correspond to light maximum whereas those of 1994 June 12 to 15 and possibly 1994 July 29 to 31 to light minimum.

The spectra at light maximum (relative to light minimum) show stronger high-excitation lines (for example He I, N I and O I) and weaker low-excitation and zero-volt lines (for

Table 1. Spectroscopic observations of R CrB.

	Date	MJD [a]	λ Range (Å)	V	B–V	U–B	Radial Vel. (km s^{-1})[b] N I	O I	C I	2.0 eV	0.0 eV
1990	Mar 17.49	7967.99	4240-4250	6.070	0.64	0.17				(23.3)[c]	
	May 8.00	8019.60	5885-5898	5.917	0.578	0.12				(24.6)[c]	
1993	Apr 29.17	9106.67	5820-5900	5.790	0.554	0.36			18.8	19.3	
1994	Feb 22.	9405.89	4000-4400	6.055	0.619	0.12			19.2	18.2	18.0
	Mar 23.31	9434.82	Na I D	5.886	0.540	0.013					
	Apr 2.46	9444.97	6100-8000	5.790	0.531	-0.007	20.8	20.3		18.0	17.7
	Apr 29.27	9471.78	6000-7900	6.080	0.633	0.110	24.5	25.5	26.0	24.8	24.9
	May 1.23	9473.73	5100-5950	6.115	0.644	0.134					d
	May 2.	9474.75	3900-4270	6.117	0.635	0.148			25.3	26.6	26.1
	Jun 12.20	9515.71	NaI D	5.96	0.591	0.125			25.8		
	Jun 13.13	9516.63	Na I D	5.969	0.594	0.130			25.1		23.2
	Jun 14.11	9517.62	Na I D	5.952	0.597	0.102					
	Jun 15.11	9518.62	Na I D	5.925	0.626				25.6		
	Jun 24.21	9527.71	5700-7800	5.831	0.566	0.087			19.9		
	Jun 26.21	9529.71	6050-8000	5.823	0.552	0.048	15.9	16.4		20.4	21.3
	Jun 27.23	9530.73	5100-5950	5.818	0.564	0.062					d
	Jul 29.17	9562.61	Na I D								
	Jul 31.10	9564.60	6100-8000				22.0	21.5	23.0	22.4	21.5

[a]MJD = Modified Julian Date.
[b]Radial velocities are given for N I, O I, C I lines and 'metal' lines with excitation near 2.0 and 0.0 eV.
[c]Radial velocity from Fernie & Lawson (1993); Gorynya, Rastorguev & Samus (1992).
[d]C_2 radial velocity: May 1.23, 20.6 km s^{-1}; June 27.23, 20.9 km s^{-1}.

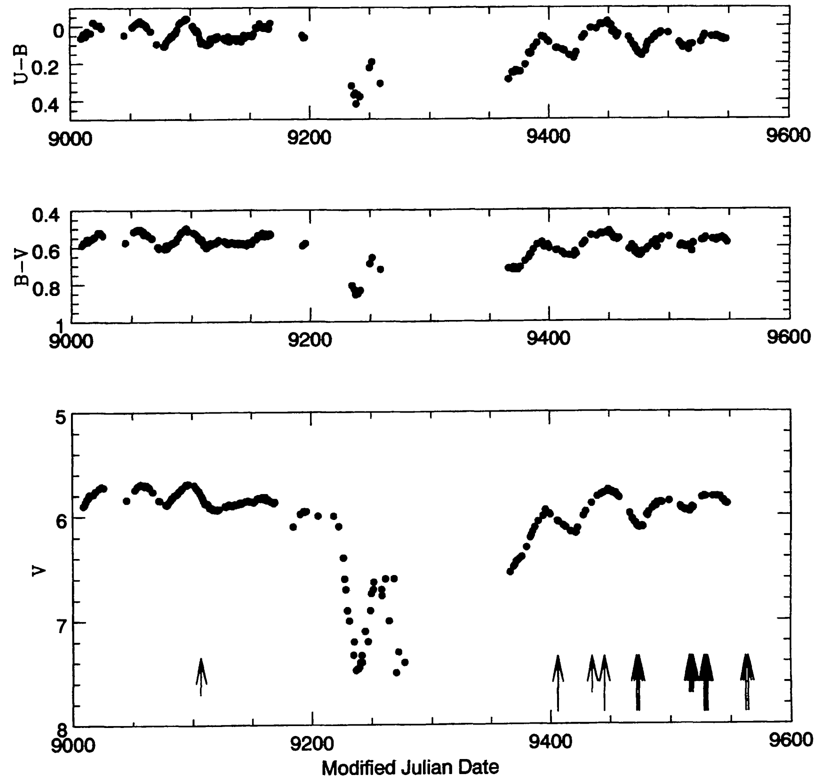

Figure 1. *UBV* photometry of R CrB from the Modified Julian Date (JD – 244 0000) of MJD = 9000 to 9550. The arrows indicate the dates on which spectra were obtained.

example Li I and [O I]). The C_2 Swan bands are present but weak. Hα appears as a symmetrical absorption line. At light minimum the low-excitation lines are stronger and the blend at 5876 Å of He I and C I is weaker. Hα shows a weak emission component accompanying the strong absorption line. The C_2 lines are very pronounced at minimum light (Fig. 2); the 0–1 bandhead at 5635 Å increased in depth from 0.2 at maximum (June 27) to 0.4 at minimum (May 1). Clayton et al. (1995) monitored the variation in molecular band strengths using low-resolution spectra and showed that they are, as here, strongest at the reddest colour (minimum light).

It is of particular interest to use these spectra from maximum and minimum light to determine the changes in physical conditions of the stellar atmosphere. Equivalent widths of selected lines were measured in the spectra obtained on 1994 April 2 (max) and 1994 April 29 and May 1 (min). Our analysis is based on model atmospheres computed specifically for RCB stars – see Gustafsson & Asplund (1996) and Asplund et al. (1996) for details. The models are built from the customary assumptions of local thermodynamic and hydrostatic equilibrium and flux constancy. Appropriate opacities are included with the Opacity Project providing accurate photoionization cross-sections for neutral carbon and other species. Line blanketing is included by a mix of opacity distribution functions and line sampling. Our method of analysis follows that devised for a comprehensive abundance analysis of RCBs using echelle spectra and the same family of model atmospheres which will be reported in detail elsewhere.

Defining parameters of the model atmosphere are the effective temperature $T_{\rm eff}$, the surface gravity g, the C/He ratio and the microturbulence ξ. With the exception of the C/He ratio, the parameters are determined from the spectra. The C/He ratio is taken as 1 per cent by number of atoms. Our primary conclusions are insensitive to this choice which seems representative of RCBs and of their possible relatives the hot extreme helium stars (Lambert & Rao 1994; Rao & Lambert 1996; Jeffery 1996). The microturbulence is determined as customary from the requirement that elemental abundances derived from a suite of lines from the same species be independent of equivalent width. Three species – Fe I, Fe II and Ca I – provide an adequate number of lines: we find $\xi = 7 \pm 1$ km s^{-1} for both epochs. The $T_{\rm eff}$ and g are estimated using a combination of constraints. One is that lines from neutral and singly ionized atoms of the same element must give the same abundance. Iron through Fe I and Fe II lines provides an adequate number of lines to define this condition of ionization equilibrium in the $\log g$, $T_{\rm eff}$ plane. Supplementary evidence is provided by Si I/Si II and S I/S II. To within expected uncertainties the Si and S loci overlap the better defined Fe locus. Another locus of different slopes is needed so that $T_{\rm eff}$ and g may be separately estimated. An estimate of $T_{\rm eff}$ was obtained from the constraint that the low-excitation [O I] 6363-Å and the high-excitation O I lines yield the same abundance. The [O I]/O I and Fe I/Fe II loci intersect at a steep angle and $T_{\rm eff}$ and g may be inferred: $T_{\rm eff}$ of 6750 ± 100 K and $\log g$ of 0.25 ± 0.2 for the maximum and $T_{\rm eff}$ of 6250 ± 100 K and $\log g$ of 0.25 ± 0.2 for the mini-

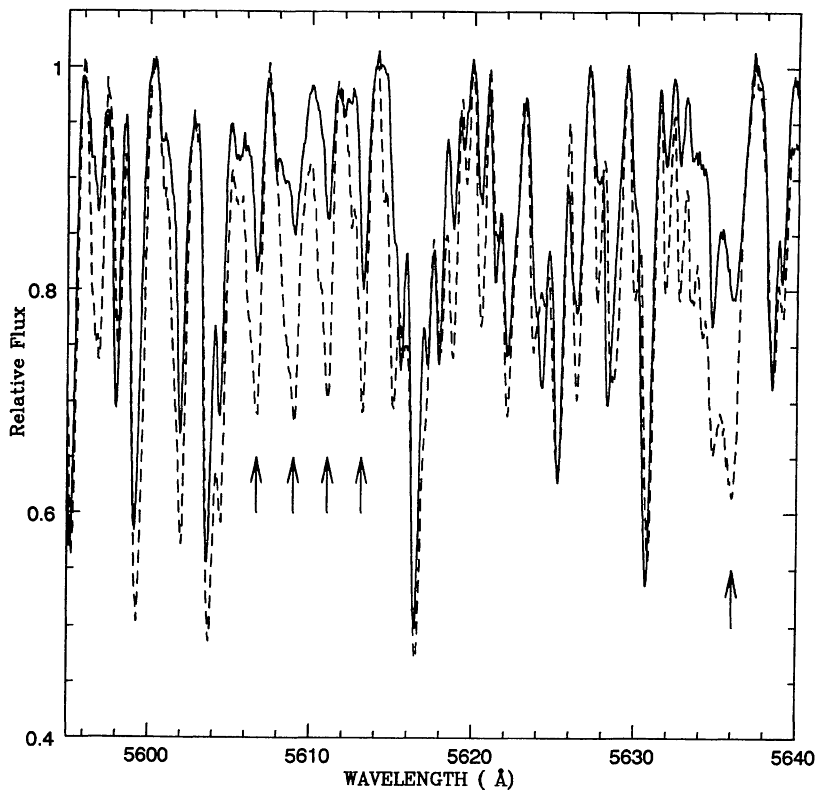

Figure 2. The C_2 Swan 0–1 bandhead at maximum light (June 27, solid line) and minimum light (May 1, dashed line). Note especially the bandhead at 5636 Å and four triplet lines from 5606–5614 Å that are obviously strengthened at minimum light.

mum.[2] The elemental abundances obtained from our spectra are identical at maximum and minimum light to within the expected uncertainties.

That the atmosphere is cooler at minimum light than at maximum light is in semiquantitative agreement with the photometric variations: the calibration of Asplund et al. (1996) of the $(B-V)$ colour suggests a 300-K difference between maximum and minimum light. The radial velocity amplitude (approximately ± 4 km s^{-1} – see below) suggests that the stellar radius varies by less than about 10 per cent between maximum and minimum light. This together with small acceleration of the atmosphere during the pulsation implies a small ($\leq \pm 0.1$ dex) change to $\log g$. Also, if the luminosity is assumed constant, the effective temperature difference between maximum and minimum light implies a 16 per cent change in surface gravity, again a change of less than 0.1 dex. Such a change is less than the spectroscopic uncertainty of ± 0.2 dex.

4 RADIAL VELOCITIES AND DIFFERENTIAL MOTIONS

We measured the radial velocities of lines of different excitation potentials and equivalent widths to check for differential motions. Spectra corresponding to maximum and minimum light were measured. The measured radial velocity refers to the line core. It is felt that line cores give a better estimate of radial velocity in turbulently broadened and blended absorption lines. Most lines at both extreme phases are symmetrical in the absence of blends with a width (FWHM) of about 30 km s^{-1} which is the true width considering that the instrumental width is about 5 km s^{-1}. The radial velocity of an individual line can be measured to an accuracy of about 2 km s^{-1}. In case of the sharper lines like the IS components of Na I D lines (Table 2) the uncertainty in the measurements is ± 0.7 km s^{-1}.

The radial velocities measured on the two occasions near maximum light (1994 April 2 and June 26) show *different* trends suggesting that either rapid changes can occur near maximum light or the velocity variations are temporally more complex than the light variations. The velocities for April 2 show a slight trend with excitation potential which we interpret as a variation of velocity with depth into the atmosphere: high-excitation lines such as the N I lines are formed much deeper than the low-excitation lines of Fe I and the resonance lines of K I and Li I. The N I lines have a radial velocity of 21 km s^{-1} whereas the low-excitation lines have 18 km s^{-1} indicating an expansion of the top relative to the base of the photosphere. The radial velocities of 71 lines with a range in excitation potential of 0 to 11.76 eV show a systematic trend with excitation potential. The slope of this trend is 0.26 km s^{-1} eV^{-1} with a correlation coefficient of 0.77 ± 0.05.

Spectra from June 26 which also refer to maximum light imply a reverse trend of velocity with depth. The high-

[2]The values of T_{eff} and g are similar to those obtained previously from analyses of spectra taken at unknown phases in the pulsational light cycle and by the use of earlier model atmospheres (Cottrell & Lambert 1982a; Pollard, Cottrell & Lawson 1994).

excitation neutral lines have a smaller radial velocity than the low-excitation lines (16 versus 21 km s^{-1}). The slope of this systematic trend determined from 38 lines is -0.40 ± 0.07 km s^{-1} eV^{-1} with a correlation coefficient of 0.79 ± 0.06. Velocity differences are well revealed by the

Table 2. Radial velocities of absorption components in the Na I D_2 and D_1 lines.

1994 Date	MJD	Component Velocity (km s^{-1}) IS	A	B	C	D
23 Mar	9434.32	(-20.5)	3.0[a]		29.9[a]	
		(-20.5)	3.4[a]		30.9[a]	
1 May	9473.73	-21.4	1.2	8.3	25.8	-63.4
		-21.6	-0.9	12.0	26.2	
12 Jun	9515.71	-20.5	0.1	13.0	32.2	-69.7
		-20.2	0.1	14.9	31.8	
13 Jun	9516.64	-20.5	0.2	12.8	32.0	
		-20.4	0.1	15.0	32.6	
15 Jun	9518.62	-20.7	-0.3	13.5	31.6	-69.4
		-20.6	-0.4	15.9	32.1	
24 Jun	9527.71	-21.7	-1.2	17.5	30.0	
		-21.7	-1.2	13.4	29.9	
27 Jun	9530.73	-19.5	-0.0	17.3	33.2	
		-19.2	1.4	15.3	31.7	
29 Jul	9562.61	-20.9	-0.2	12.8	27.4	
		-21.2	0.4	15.0	28.0	

[a]Velocities of the components A and C were measured with respect to the IS components and adjusted to the IS velocity of -20.5 km s^{-1}.

trend of radial velocity with equivalent widths of the lines – Fig. 3 shows the trends for C I and Fe II lines (excitation potentials of 2.9 to 6.2 eV) for this date and for April 2. The cores of the stronger lines are presumably formed in the upper layers of the photosphere and the weaker lines in the deeper layers. This is especially true for the C I lines which differ little in excitation potential. On June 26, the radial velocity differential was about 10 km s^{-1} between the weak ($W_\lambda \simeq 100$ mÅ) and strong ($W_\lambda \simeq 500$ mÅ) lines. The high-excitation lines of N I and O I have, as expected, the same velocity (about 16 km s^{-1}) as the weakest Fe II and C I lines. Similar plots of W_λ versus radial velocity for April 2 show much less distinct trends: there is possibly a velocity difference between strong ($W_\lambda \simeq 300$ mÅ) and weak ($W_\lambda \simeq 200$ mÅ) lines of -2 km s^{-1} for C I and $+4$ km s^{-1} for Fe II lines.

At light minimum, as represented by the spectra obtained on 1994 April 29/May 1 and July 31, the atmosphere appears without differential motions, (Fig. 4); radial velocities of 65 lines (April 29) and 46 lines (July 31) show that they are independent of equivalent width, excitation potential, and whether the carrier is a neutral atom or an ion. (The slopes with respect to excitation potential are 0.09 ± 0.09 and 0.06 ± 0.06 km s^{-1} eV^{-1}.) The mean velocity is similar to the most positive of those measured at light maximum. At light minimum the C_2 molecular lines have a smaller velocity relative to the atomic lines by 5 km s^{-1} which suggests the layers in which the molecular lines are formed are expanding relative to the deeper layers. At light

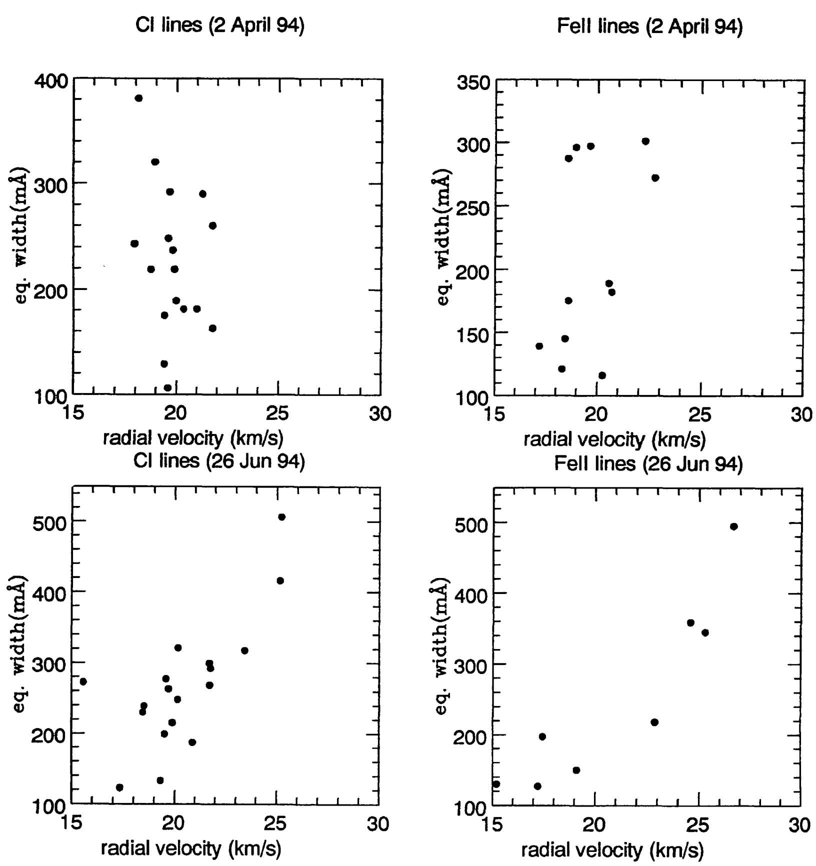

Figure 3. Equivalent width and radial velocity correlations for two occurrences of maximum light (April 2 and June 26).

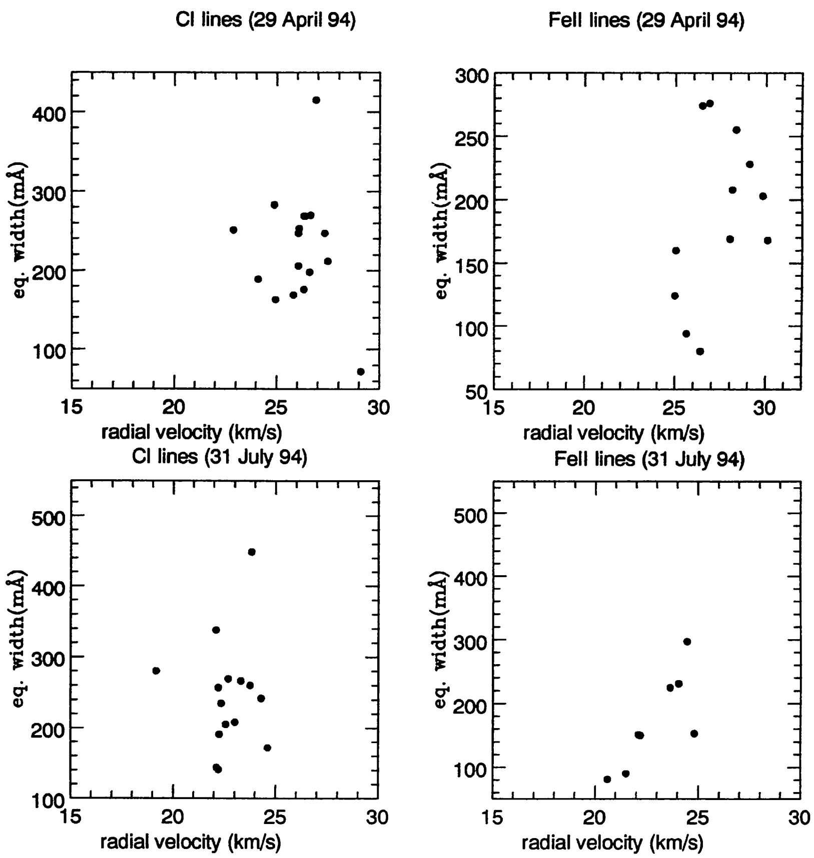

Figure 4. Equivalent width and radial velocity correlations for two occurrences of minimum light (April 28 and July 31).

maximum there is no such difference between atomic and molecular lines.

The systematic velocity can best be represented by the radial velocities of high-excitation lines (for example N I), which show a range of 16.2 ± 1.8 km s^{-1} to 24.8 ± 2.0 km s^{-1}, and the mean of 20.5 km s^{-1} is taken as the systemic velocity.

5 Hα EMISSION

Although a considerable deficiency of hydrogen is a trademark of RCBs, the Balmer lines are weakly present in the spectrum of R CrB. Fig. 5 shows the region around Hα in the pair of spectra taken at light maximum and light minimum. At maximum and minimum light, Hα at 6563 Å is a prominent absorption line. Weak emission in the blue wing is clearly seen in both spectra from minimum light. The emission has a blueshift of 70 km s^{-1} relative to the absorption line core of Hα which has the velocity of other photospheric lines such as the C I and Fe II lines. The absorption component of Hα is not drastically changed when the emission appears which suggests that the detected emission may be the entire signature of the emitting gas; stronger emission is not filling in the absorption line. Emission is not present at the 1994 April 2 maximum but possibly weakly present at the 1994 June 26 maximum.

This emission might arise from shock heating resulting from the differential motion of the photosphere. It might also come from an extension of the atmosphere region such that off-limb regions provide the emission In the latter case, however, one expects the emission to be approximately centred on the mean photospheric velocity not blueshifted by 70 km s^{-1}. Moreover the spectrum obtained in a deep decline does not show Hα emission, as should be the case if the emission seen here is chromospheric or from a more extended region.

6 LINE SPLITTING

RY Sgr shows line splitting at pulsation light maximum – a result of an atmospheric shock dividing the photosphere into two parts of different velocity (Cottrell & Lambert 1982b; Lawson 1986; Clayton et al. 1994). The splitting is conspicuous with respect to magnitude and ubiquity: it amounts to about 40 km s^{-1}, equivalent to more than the width of the unsplit lines, and essentially all the photospheric lines are split. No such line splitting is present in any of our spectra of R CrB at light maximum or at other phases. Strong lines of C I, Ba II 5853 Å, Fe II 6369 Å, Si II 6347 Å, Ti II 6559 Å which were seen in RY Sgr as split are defiantly single. Strong lines at the June 26 maximum are asymmetric as expected for an atmosphere with a pronounced velocity gradient. At the April 29 minimum, the same lines are symmetric.

Reports of line doubling (i.e., splitting) in R CrB do exist. These refer to very strong lines in the blue. The Sc II line at 4247 Å was reported as double by Gaposchkin (1963). Re-examination of this line showed an apparent doubling at

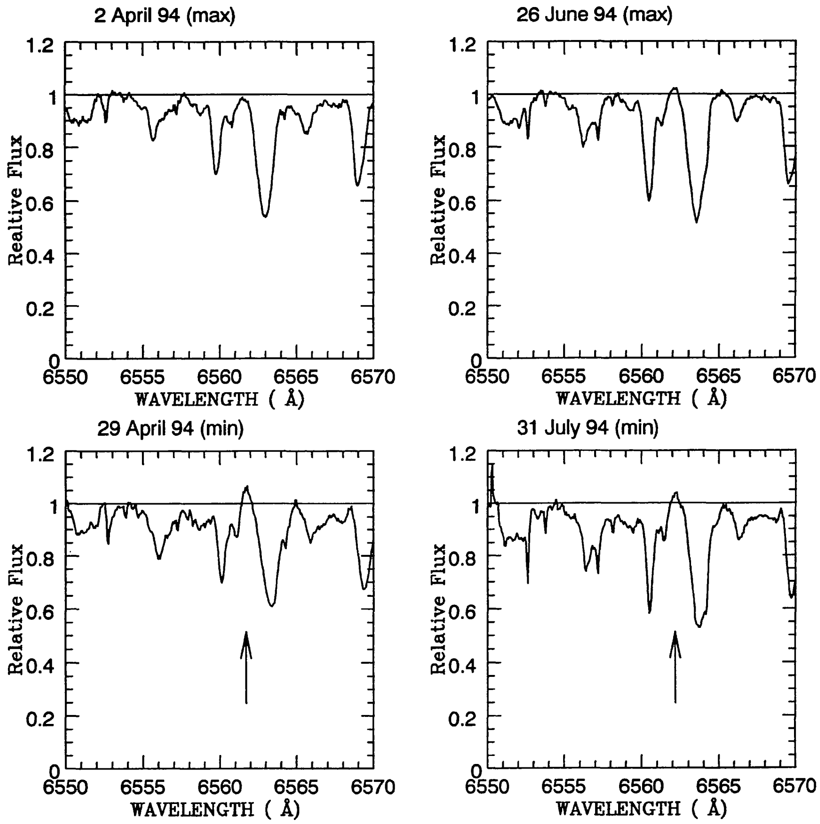

Figure 5. The region around Hα in maximum and minimum light spectra. Note the appearance of emission in the blue wing of Hα in the minimum light spectra. The few very narrow lines in these spectra are telluric H_2O lines.

maximum light (see the illustration in Lambert et al. 1990). The Sc II line is present as double in all of our blue spectra. The separation of the components seems to change. In 1990 March (close to minimum – Fernie & Lawson 1993) the absorption components were at 12 and 32 km s^{-1}. On February 22 (midway in the descent to minimum) the velocities were 4 and 32 km s^{-1}, and on May 2 (minimum) the velocities were 7 and 30 km s^{-1}. The splitting seems to be centred around the mean velocity of the star.

It is not clear that this doubling is at all related to a shock. Earlier it was suggested that the Sc II 4247-Å doubling arose from a chromospheric emission core overlying the photospheric absorption line (Gaposchkin 1963). Lambert et al. (1990) echoed this view. It is also possible that there is a second absorption component but that this arises from gas above the photosphere. If this surmisal is valid, this gas ought to be seen more readily in resonance lines of more abundant species, such as the Na D lines.

7 Na I D LINES – ABSORPTION COMPONENTS

Dramatic changes were noticed in the high-resolution profiles of the Na I D lines recorded in 1994 March relative to our previous observations in 1990. Appearance of extra blueshifted components in the 1994 March 23 spectrum relative to the 1990 May spectrum (Fig. 6) led to this programme of spectroscopic monitoring. A montage of our Na D spectra is shown in Fig. 7. Note that the spectra are not all of the same resolution. In the highest resolution spectra obtained with the Tull spectrometer the likely interstellar line (marked IS in Fig. 7) is partially resolved into two components. In the Sandiford spectra obtained at about half the resolution of the Tull spectrometer, the line doubling is not seen. This difference in resolution is of no serious consequence here.

There seem to be four components contributing to the Na D profiles (apart from the likely interstellar lines marked IS). We label the components A, B, C and D in Fig. 7 and give their radial velocities in Table 2. The radial velocities are measured from the centre of the absorption dips in the profiles. Some of the spectra, particularly the high-resolution spectra, have been divided by a hot star to remove the telluric (H_2O) lines. Stellar absorption dominates component C. Components A, B and D are here described as circumstellar. (A weak component E marked in Fig. 6 makes a few appearances.)

Component A, which appears not to change its central depth (relative to the IS components) over our sequence of observations, has a constant velocity of 20 ± 1.3 km s^{-1} as measured with respect to the IS lines or a heliocentric velocity of 0.4 ± 1.3 km s^{-1}. Not surprisingly given the 20 km s^{-1} difference between its velocity and the mean photospheric velocity, A is immune to the photospheric velocity variation. We suppose A is formed in a detached shell. (The component is also seen superimposed on the Na I D emission lines in the 1995 October deep minimum.)

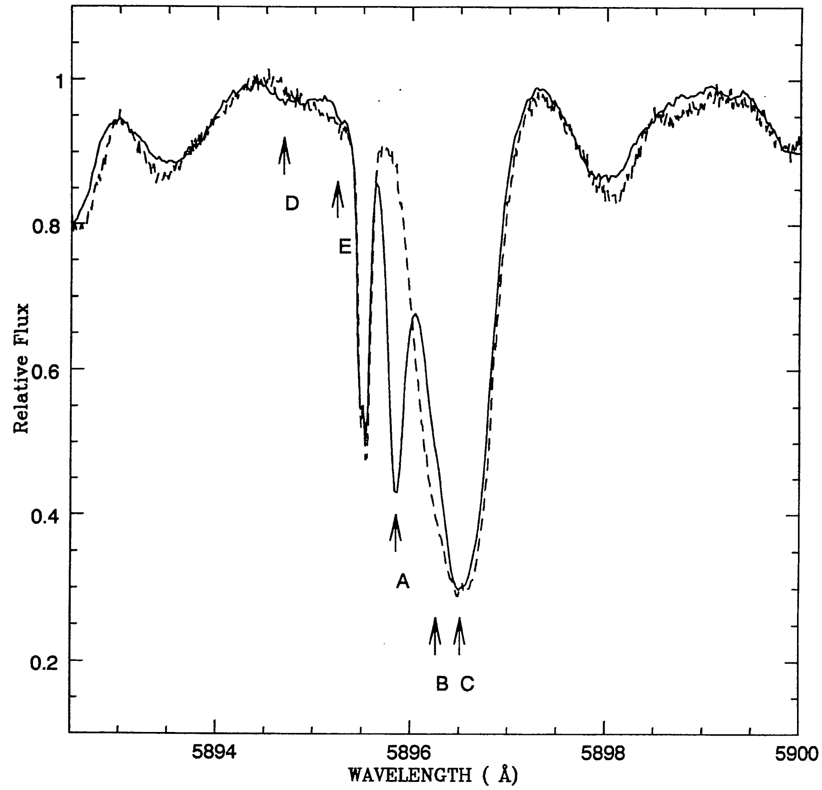

Figure 6. The profiles of Na I D 5896-Å line obtained on 1990 May (dashed line) and 1994 March (solid line) are superposed. The arrows mark the positions of circumstellar absorption components A to E. Some of them, particularly A, were not present in 1990 spectrum.

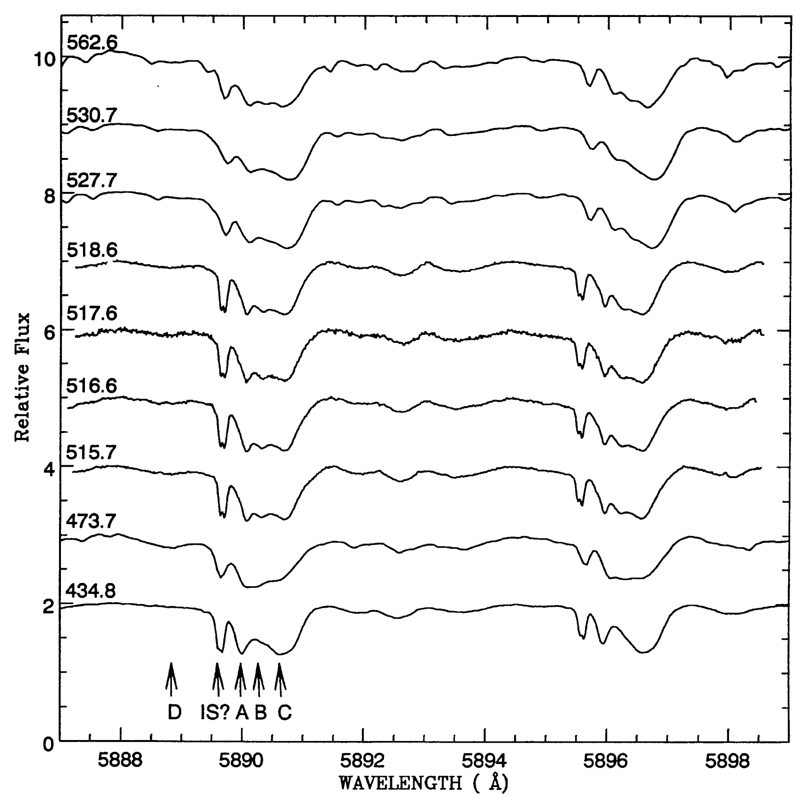

Figure 7. A montage of the Na D lines. The date of the observation (MJD – 9000) is given on the left-hand side. Components C (primarily photospheric) and A, B and D (all 'circumstellar') are discussed in the text. The blueshifted strong component is likely of interstellar origin (marked IS?).

Component B also shows a constant radial velocity: 36 ± 2 km s^{-1} relative to the IS components or a 6 ± 2 km s^{-1} mean blueshift relative to the photosphere. In contrast to A, the intensity of B (or an overlying subcomponent) varies being strongest at minimum light.

Component C unlike either A or B shows a velocity variation indicative of periodic variations corresponding to the pulsations. Thus, we suppose that C is primarily the photospheric Na D line but it may be blended with a shell component since its mean radial velocity (30 ± 2 km s^{-1}) is larger than that expected for the photosphere as measured by the high-excitation lines (20 km s^{-1}).

Component D is a weak feature which appears strongest near or at minimum light: it is strong on May 1 (minimum) but absent on March 23 and again on June 24 and 27 (maximum or close to it), again strong on June 12 to 15 (minimum) and July 29 (close to the minimum). Component D is blueshifted by about 90–95 km s^{-1} with respect to the stellar photospheric lines. At this velocity, the gas of component D will leave the star unless decelerated appreciably.[3] We do not have enough coverage to comment on the duration of component D during a pulsation cycle.

Our sequence of observations suggests component A to be a shell line. A suspicion that the shell is a by-product of the deep light minimum that occurred in 1993 July (Fig. 1) may be checked by comparing our spectra with that presented by Lambert et al. (1990) and obtained with the Tull spectrometer prior to the 1993 decline: Fig. 6 clearly shows A was *not* present in 1990. A lower resolution spectrum obtained of the Na D lines on 1993 April 29 was superimposed on the 1994 March 23 spectrum degraded to the lower resolution. Fig. 6 shows that component A was also not present in 1993 April. Therefore, we think it likely that A was ejected during the deep decline in late 1993. Any changes in the strength of component A because of shell expansion are not easy to discern. Comparison of the 1994 March 23 profile with 1994 June 12–15 profiles show a strengthening of A in June spectra, but the component B also got much stronger in the June spectra.

8 DISCUSSION

Although temporal coverage was not intensive, several interesting facets of R CrB's variability have been revealed here. A brief commentary on them and their interpretation follows.

The semiregular atmospheric pulsation with period in the range 30–50 d results in a cooler atmosphere at minimum than at maximum. Using model atmospheres we determine the effective temperature difference to be 500 K and the surface gravity to be effectively constant. Measurements of radial velocities imply the presence of a pronounced velocity gradient in the atmosphere at maximum light. Velocity differences between lines are not seen in all spectra obtained close to maximum light, apparently the gradient exists for no more than a brief interval near maximum light or does not occur at each pulsation.

Emission in the blue wing of Hα may be due to a shock driven by the pulsation. If the measured emission velocity is that of the shock, it is moving out at a high Mach number: the velocity is 70 km s^{-1} in an atmosphere where the sound velocity is 5 km s^{-1}. Attribution of the emission to a shock is preliminary. We do note that Hα emission is considered a tracer of shocks in RV Tauri and W Virginis stars (Abt 1954; Preston 1962; Baird 1982; Raga, Wallerstein & Oke 1989). The similarity of the pulsations in RV Tauris, W Virginis and R CrB has been noted by several investigators (for example, Fernie, Sherwood & DuPuy 1972; Howell, Bopp & Noah 1983; Baird 1984). Our measured radial velocity for Hα emission is similar to that reported for some RV Tauris: Gillet et al. (1989) measured a blueshift (relative to the photosphere) of up to 50 km s^{-1} for R Sct. Continued searches for evidence of shocks and measurement of shock diagnostics might be sought in the ultraviolet where the photosphere is dark. It will, however, be difficult to obtain intensive temporal coverage in order to monitor growth of the shock. None the less, the effort is worthwhile because Goeres & Sedlmayr (1992) and Woitke et al. (1996) emphasize that shocks appear necessary for the growth of dust grains in RCB atmospheres. Thus, shocks may be one part of the trigger mechanism that puts an RCB into a deep decline.

Shocks are believed to be responsible for the pronounced line splitting that occurs during the pulsation of RY Sgr. In sharp contrast, comparable line splitting has never been reported for R CrB and certainly it is not detected in our sequence of high-resolution high-quality spectra. Line doubling seen here and previously in very strong absorption lines in the blue may be either a restricted manifestation of real splitting of a photospheric line or an apparent splitting resulting from overlying chromospheric emission. Since sharp 'chromospheric' lines are the first emission lines to appear during a decline, the latter explanation seems the more probable of the two. It remains to be understood why line splitting so evident in RY Sgr is absent from R CrB when the two stars appear so similar. The key is likely that RY Sgr has a larger velocity amplitude.

An understanding of pulsation, shocks and line splitting requires observations – spectroscopic and photometric – closely spaced in time and spanning at least a few pulsations. Our study of the multicomponent Na D profiles shows in contrast that full understanding of R CrB's upper atmosphere will require longer term studies too; for example, component A, which is considerably Doppler shifted from the photospheric velocity, may be a remnant of the 1993 deep decline. If, as is widely supposed, a deep decline of R CrB follows the formation of a dust (and gas) cloud along the line of sight, we may identify component A as the gaseous component of the cloud responsible for the decline in late 1993. Since the velocity of A relative to the photosphere exceeds the escape velocity at a few stellar radii above the photosphere, it is likely component A has been ejected.

The dust–gas cloud was formed above the photosphere at 2 to 20 stellar radii. Acceleration was driven by radiation pressure on the grains with the gas dragged along by dust–

[3]The escape velocity is about 70 km s^{-1} for an assumed mass of 1 $M_\odot$ and a stellar radius of $R_* \simeq 80$ $R_\odot$ where the latter assumes $M_{bol} = -5$ (Feast 1979) and $T_{eff} = 6500$ K. The escape velocity may also be written as $v_{esc} = \sqrt{gR_*}$ where $\log g \simeq 0.3$ and $T_* \simeq 80$ $R_\odot$ give $v_{esc} \sim 30$ km s^{-1}. The two estimates may be reconciled by reducing the adopted mass ($\mathcal{M} \sim 0.6$ $M_\odot$ is a likely minimum value) and/or adopting a more luminous M_{bol}.

gas collisions. The higher outward velocity of the dust relative to the gas leads to a separation of the initial cloud into a dust moving ahead of a gas cloud. The initial (d) size of the cloud must be approximately a stellar diameter in order to cause a deep decline. The instantaneous thickness of the cloud is presumably smaller. If it is formed close to the star (say at $R \sim 2R_*$), the instantaneous thickness is likely to be a small fraction of R_*. On the other hand, if dust forms at a greater distance (say at $R \sim 20R_*$), the instantaneous thickness might be comparable to R_*. The thickness of the final cloud (h_{cl}) depends on the duration of the episode of dust formation. If the relative velocity of dust and gas is Δv, the separation of dust and gas is achieved on a time-scale $t_{sep} \sim h_{cl}/\Delta v$. If $h_{cl} \sim R_* \sim 80\ R_{\odot}$, $t_{sep} \sim 2/\Delta v$ for t_{sep} in yr and Δv in km s^{-1}. Since Δv is likely to exceed a few km s^{-1} either initially or after the cloud has internally expanded, it is clear that the dust ought to separate quickly from the gas.

Quite possibly such a separation occurred before our first observation of component A. Then, it may be surprising that the gas devoid of grains shows a nearly constant outward velocity. (Radiation pressure through the Na D and other resonance lines may also drive the gas outwards.) The time-scale for gravitational deceleration is $\Delta t \sim v_0/g$ where v_0 is the velocity of the gas at the separation of dust and gas, and $g \simeq g_*(R_*/R_{sep})^2$ is the gravitational acceleration at the height R_{sep} of dust–gas separation. Plausible values are $R_{sep} \geq 10R_*$, $g_* \sim 2$ cm s^{-2} and $v_0 \sim 30$ km s^{-1} (the present value). Then, $\Delta t \sim 5$ yr, i.e., a constant velocity over the 1994 observational season is not unexpected. Spectra obtained in 1995 February show that component A has either weakened considerably since 1994 July or been Doppler shifted to the red and blend with the variable strong blend of components B and C. The redshifting is certainly consistent with infalling gas. Component A, which may have ended its existence as a distinct cloud by returning to the photosphere, may have begun as high-velocity ejection such as was seen in the 1990 decline (Lambert et al. 1990).

R CrB and other stars of the class continue to present stiff challenges to observers. The logistical problems of obtaining thorough spectroscopic coverage in time and wavelength are servere. We hope that the results obtained here from less than optimum coverage encourage more detailed studies.

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