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R Coronae Borealis at the 2003 Light Minimum*

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ABSTRACT

A set of five high-resolution optical spectra of R CrB obtained in 2003 March is discussed. At the time of the first spectrum (March 8) the star was at V = 12.6, a decline of more than six magnitudes. By March 31, the date of the last observation, the star at V = 9.3 was on the recovery to maximum light (V = 6). The 2003 spectra are compared with the extensive collection of spectra from the 1995-1996 minimum presented previously. Spectroscopic features common to the two minima include the familiar ones also seen in spectra of other RCBs in decline: sharp emission lines of neutral and singly-ionized atoms, broad emission lines including He I, [N II] 6583 Å, Na D, and Ca II H & K lines, and blueshifted aborption lines of Na D, and K I resonance lines. Prominent differences between the 2003 and 1995-1996 spectra are seen. The broad Na D and Ca H & K lines in 2003 and 1995-1996 are centred approximately on the mean stellar velocity. The 2003 profiles are fit by a single Gaussian but in 1995-1996 two Gaussians separated by about 200 km s^{-1} were required. However, the He I broad emission lines are fit by a single Gaussian at all times; the emitting He and Na-Ca atoms are probably not colocated. The C_2 Phillips 2-0 lines are detected as sharp absorption lines and the C_2 Swan band lines as sharp emission lines in 2003 but in 1995-1996 the Swan band emission lines were broad and the Phillips lines were undetected. The 2003 spectra show C I sharp emission lines at minimum light with a velocity changing in five days by about 20 km s^{-1} when the velocity of 'metal' sharp lines is unchanged; the C I emission may arise from shock-heated gas. Reexamination of spectra obtained at maximum light in 1995 shows extended blue wings to strong lines with the extension dependent on a line's lower excitation potential; this is the signature of a stellar wind, also revealed by published observations of the He I 10830 Å line at maximum light. Changes in the cores of the resonance lines of Al I and Na D (variable blue shifts) and the Ca II IR lines (variable blue and red shifts) suggest complex flow patterns near the photosphere. The spectroscopic differences at the two mimima show the importance of continued scrutiny of the declines of R CrB (and other RCBs). Thorough understanding of the outer atmosphere and circumstellar regions of R CrB will require such continued scrutiny.

Key words: Star: individual: R CrB: variables: other

1 INTRODUCTION

R Coronae Borealis stars (here, RCBs), a class with about 30 Galactic members, are H-poor supergiants that decline in brightness unpredictably and rapidly by up to 8 magnitudes to remain at or near minimum light for several weeks to months. Although it is generally accepted that the declines are due to formation of an obscuring cloud of carbon soot (Loreta 1934; O'Keefe 1939), many questions remain unanswered about the formation and evolution of the dust clouds (Clayton 1996). The discovery that RCBs possess an infrared excess even at maximum light suggested that a swarm of dust clouds is a permanent feature (Feast 1975, 1979, 1986). Dust forms over a part of the star. If it forms over the Earth-facing hemisphere, a decline ensues. Often,

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the dust forms at other locations and then no (or a weak) decline will be seen. Recently, dust clouds have been directly imaged in the infrared at 2.17 and 4.05 microns around the RCB star RY Sgr (de Laverny & Mékarnia 2004).

Spectroscopic observations of RCBs in decline, when the stellar photosphere is heavily obscured, have the potential to provide novel and unique information about the outer stellar atmosphere and circumstellar region. To date, high resolution spectroscopic optical observations of RCBs in deep declines have been limited in number and scope. We are attempting to gather spectra of RCBs in deep declines, as opportunities arise. Our goals are twofold: (i) to obtain at least one high-resolution optical spectrum of as many RCBs in decline as possible, and (ii) to observe several deep declines of the brightest RCBs with an emphasis on the prototype R CrB, which is readily accessible from the McDonald Observatory.

Here, we report on spectra obtained during the 2003 decline of R CrB and, in particular, we compare and contrast the spectra with those obtained during our intensive coverage of the star's 1995-1996 decline (Rao et al. 1999). The 2003 minimum was well separated in time from the preceding one that occurred in 2001. (A brief spectroscopic account of the recovery from the 2001 minimum has been given by Kipper (2001).) Our sequence of five high-resolution spectra of R CrB was obtained in 2003 March during and following the deep minimum.

The light curve obtained from the AAVSO and Efimov (2004 -private communication) shows that the star started to decline on or about 2003 February 9. The decline was rapid reaching V $\simeq$ 12.9 by March 1. The star was fainter than V $\simeq$ 12.5 for about two weeks from late February to March 17 and then brightened gradually reaching V $\simeq$ 9.4 by March 31. The visual light curve from onset of the decline through to recovery almost to maximum light is shown in Figure 1 with the times at which our five spectra were taken indicated by arrows. The first two spectra were acquired when the star was at minimum light at V $\simeq$ 12.5. The third spectrum was taken in the early stages of recovery to maximum light with the star at V $\simeq$ 10.7. The final pair of spectra was taken when the star had brightened to V $\simeq$ 9.3. At maximum, R CrB is at V = 6. During the 1995-1996 decline, R CrB faded to V = 13.6.

2 OBSERVATIONS

Our first two spectra were taken with the queue-scheduled 9.2 meter Hobby-Eberly Telescope (HET) and its High-Resolution Spectrometer (Tull 1998) These HET spectra are at a resolving power of $R = \lambda/d\lambda \simeq 60000$ and provide full wavelength coverage from 5320 Å to 7330 Å.

The remaining three spectra were acquired with the McDonald Observatory's Harlan J. Smith 2.7 meter telescope and the *2dcoudé* cross-dispersed echelle spectrometer (Tull et al. 1995). These observations, which were obtained when R CrB was recovering from the minimum, cover the interval 3700 Å to 10000 Å with complete spectral coverage shortward of about 5500 Å. The resolving power was $R \simeq 60,000$, as measured from the thorium lines in the Th-Ar hollow cathode comparison spectrum.

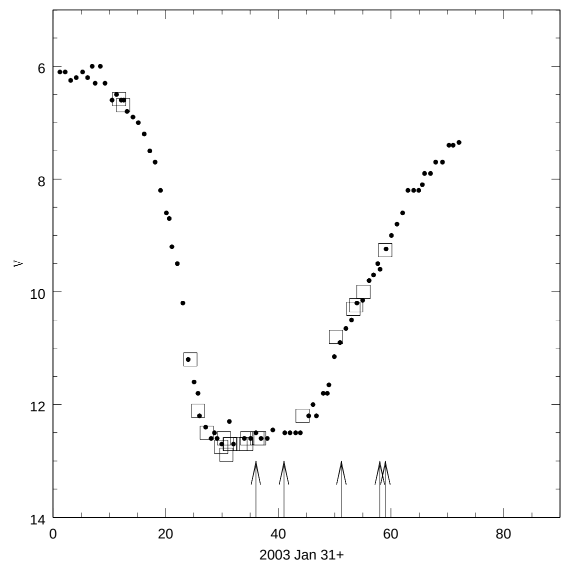

Figure 1. The light curve of R CrB for the 2003 minimum. Magnitude estimates are from the AAVSO (circles) and Efimov (2004, private communication) (open squares). The x-axis is in days with the origin at 2003 January 31. Arrows denote the times of our five spectroscopic observations

3 SPECTROSCOPIC SIGNATURES OF A RCB IN DECLINE

For a RCB in decline, emission lines dominate the optical spectrum. Two broad classes of emission lines are present: a rich set of sharp lines (FWHM $\sim$ 12 km s^{-1}), and a sparse and diverse set of broad lines (FWHM $\sim$ 300 km s^{-1}) (Herbig 1949; Payne-Gaposchkin 1963; Alexander et al. 1972). Sharp lines are primarily low-excitation transitions of singly-ionized and neutral metals that appear very early in the decline and only disappear late in the recovery to maximum light (Rao et al. 1999). The broad lines, which are seen only when a RCB has faded by several magnitudes, may include lines of the He I triplet series,Ca II H and K, K I resonance lines at 7664Å and 7699 Å, Na I D lines, [O II],and [N II] lines, i.e., a mix of high and low excitation lines with differing broad profiles (Rao et al. 1999) suggesting that there may be perhaps three regions responsible broad emission lines.

The photospheric absorption line spectrum also changes during a decline. In deep minima, the photospheric absorption lines are 'veiled', i.e., the lines become very shallow and broad. New absorption features may also appear. Broad blueshifted absorption components have been seen to accompany commonly the Na D lines, and occasionally the K I 7664 Å and 7699 Å resonance lines, and the Ca II H and K lines.[†] The Na D absorption components appear especially at and following minimum light.

Descriptions of the emission and absorption lines in de-

[†] Whitney, Dupree & Zucker (1993) claim absorption components for the Ca II K line at -240 and -180 km s^{-1} even at maximum light. These features correspond to the position of Fe I lines at 3930.3 Å and 3931.1 Å. Moreover, these blueshifted absorption features are not obvious in H line.

Table 1. Observations of R CrB in 2003

Date (UT)	Julian Date (2452000+)	Magnitude	Telescope
March 8	706.794	12.6	HET 9.2m
March 13	711.794	12.5	HET 9.2m
March 23	721.780	10.7	McDonald 2.7m
March 30	728.857	9.4	McDonald 2.7m
March 31	729.864	9.3	McDonald 2.7m

cline rest largely on high resolution spectroscopic data gathered at declines of the two brightest RCBs – R CrB and RY Sgr (Payne-Gaposchkin 1963; Alexander et al. 1972; Cottrell, Lawson, & Buchhorn 1990; Rao et al. 1999; Kipper 2001). Other RCBs observed on one or a few occasions provide useful information toward establishing a model of a RCB's outer atmosphere and circumstellar envelope. Published reports of spectra of other RCBs in decline refer to S Aps (Goswami et al. 1997), V854 Cen (Whitney et al. 1992 ; Rao & Lambert 1993, 2000; Skuljan & Cottrell 2002), and UW Cen (Rao, Reddy, & Lambert 2004).

The ubiquity of the sharp and broad emission and the blue-shifted absorption Na D lines across the sample of RCBs is unknown at present. Probably, the sharp emission lines of ionized and neutral metals are a common feature of all declines of all RCBs (Skuljan & Cottrell 2004).‡ Since few RCBs have been observed in deep minima, reported sightings of broad lines are rare. One observation worthy of particular note, if applicable to all RCBs, is Whitney et al.'s discovery that the Na D broad emission from V854 Cen is unpolarized at a time when the continuum is markedly polarized. This strongly suggests that the Na D broad emission is not viewed through the dusty cloud responsible for the decline.

Detailed descriptions of spectra of the same RCB at different declines are rare in the literature. Here, we compare the 2003 spectra with those from our extensive

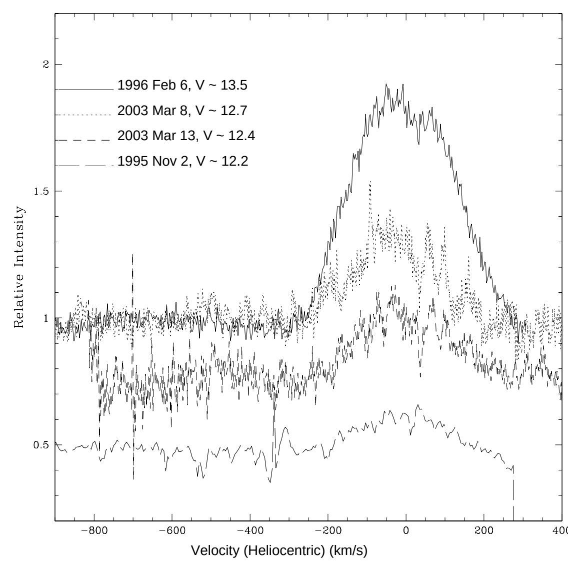

Figure 2. The He I line at 7065 Å on 2003 March 8 and 13 flanked by the profiles observed on 1995 November 2 and 1996 February 6. The spectra are ordered top to bottom by the V magnitude of the star at the time of observation. The V magnitudes are given on the figure. In this and subsequent figures a constant shift in relative intensity has been applied to the spectra for clarity.

4 EMISSION LINES

4.1 The Broad Emission Lines

Broad emission lines seen in 2003 include lines of He I at 3889 Å, 5876 Å, and 7065 Å, the Na I D lines, the Ca II H & K lines, and the [N II] line at 6583 Å. These are the strongest lines anticipated from our earlier work on R CrB (Rao et al. 1999) and V854 Cen (Rao & Lambert 1993). Other lines would surely have been seen had the spectra been of higher S/N ratio.

4.1.1 He I lines

Broad emission due to He I at 7065 Å is clearly seen in the HET spectra for March 8 and 13. The 5876 Å line is weakly present in the March 8 spectrum. Figure 2 compares the 7065 Å profiles with two observations made during minimum light in the 1995-1996 decline with all spectra normalized to a local continuum. The He I line appears strongest (relative to the local continuum) in the 1996 February 6 observation probably because the star was then a magnitude fainter (V $\simeq$ 13.5) than in 2003 March; The 7065 Å line is not seen in the spectra from March 23 and 31. This is surely because the star had brightened by two magnitudes or more so reducing the line to continuum contrast.

At the minimum of the 1995-1996 decline, the 7065 Å line appears with a quasi- parabolic profile (see the 1996 February 6 profile in Figure 2). The apparent irregularities in the 2003 profiles are attributable to the lower S/N ratio of these spectra which may be contaminated with telluric H_2O lines. The 1995-1996 spectra were ratioed with spectra of a hot star to remove the contaminating H_2O lines. The radial velocity of the 2003 emission peak (approximately the centre of the profile) is -38 km s^{-1} (Table 2). The emission extends from -250 km s^{-1} to $+190$ km s^{-1} with a width (FWHM) of 251 km s^{-1}. In 1996, the peak emission was at

‡ Emission lines of C I and O I first seen early in R CrB's 1995 decline may have been missed in other declines of R CrB and other RCBs simply for lack of appropriate observations at early times.

Table 2. Radial Velocities (km s^{-1}) of various features at the 2003 minimum of R CrB.

Feature		Date			
		March 8	March 13	March 23	March 31
Absorption lines		30.4 (17)[a]	16.9 (9)	17.8 (42)	13.5 (45)
		±2.3	±1.6	±3.4	±1.5
Sharp emissions		19.1 (79)	22.1 (80)	23.1 (29)	22.1 (20)
		±1.5	±2.7	±1.7	±2.7
	[O I]	18.3	23.8	23.4	
	[Ca II]	19.5 (2)	19.3 (2)	23.0 (2)	24.2 (2)
Shell absorption	Na I D	−93	−96	−115	−132
Broad He I emission					
	3889Å			−38.6	
	5876Å	−37.7			
	7065Å	−38.4	−38		
C_2 (Phillips)					
(2-0) absorption				9.6 (6)	

[a]The values given in parenthesis refer to the number of lines used

−13 km s^{-1} and the FWHM of the parabolic-like profile was 271 km s^{-1}.

The He I 3889 Å line is outside the wavelength range recorded on the HET spectra but it is prominent in the McDonald spectrum obtained on 2003 March 23 (Figure 3) but has almost disappeared by March 30-31. The 3889 Å line appears to be symmetrical apart from the superposition of the sharp lines. Figure 3 shows the 2003 March 23 profile with two from the 1996 decline. The blue wings of the 2003 March 23 and the 1996 May 6 profiles are blended with one and possibly two sharp lines. The bluemost of this pair is the Fe I line at 3886.3 Å. The other sharp line may be a Fe I line at 3887.1 Å. The profiles for 3889 Å and 7065 Å profiles on 1996 February 6 are quite similar; note especially the similar shape at the lines' peak. The radial velocity for the 2003 He I line is estimated to be −39 km s^{-1}, a similar value to that from the 7065 Å line. The radial velocity was -14 km s^{-1} for the 1995-1996 minimum.

The flux in a He I line may be estimated from the UBVRI magnitudes interpolated to the dates of our observation and the flux calibration suggested by Wamsteker (1981). The flux in the 7065 Å line is 6.0±0.1 $\times 10^{-14}$ erg cm^{-2} s^{-1} on March 8 and 13. The flux in the 3889 Å line is 4.5±0.6$\times 10^{-13}$ erg cm^{-2} s^{-1} on March 23. Fluxes similarly estimated for the 1995-1996 minimum were 7.2±0.2$\times 10^{-14}$ erg cm^{-2} s^{-1} for 7065 Å and 3.8±0.3 $\times 10^{-13}$ erg cm^{-2} s^{-1} for the 3889 Å line. These estimates show that the He I fluxes have changed little between the two minima. Rao et al. (1999) noted that little change occurred over the time the lines were visible during the 1995-1996 minimum. It would appear that the flux emitted in the He I lines may be independent of the ongoing decline and an intrinsic characteristic of the circumstellar shell.

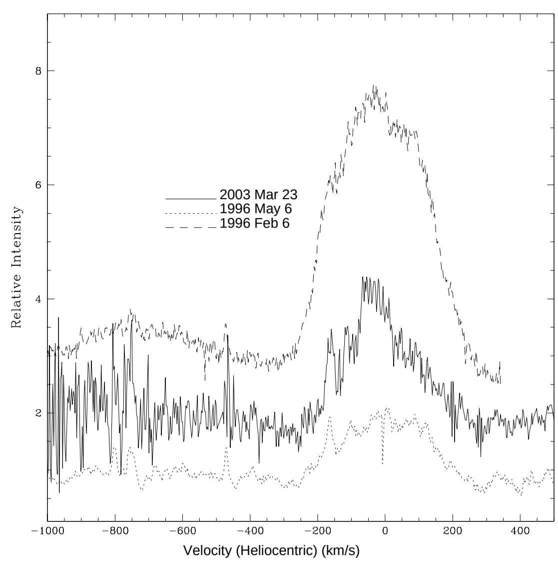

Figure 3. The He I line at 3889 Å on 2003 March 23 (solid line), 1995 May 5 (dotted line) and on 1996 February 6 (dashed line).

4.1.2 Na I D lines

Each of the Na D lines consists of a sharp component blended with a broad component, a combination seen in the 1995-1996 decline and for other RCBs caught in decline. The blue wing of D1's broad component is blended with the red wing of D2's broad component. Figure 4 shows the Na D profiles for 2003 March 8, 13, 23, and 31 plotted to bring out the growth of the blue-shifted absorption.

The blue-shifted absorption is first suspected in the March 8 spectrum where it is superposed at −93 km s^{-1} on the blue wing of the broad D2 emission. In subsequent spectra, this absorption becomes more prominent and shifts

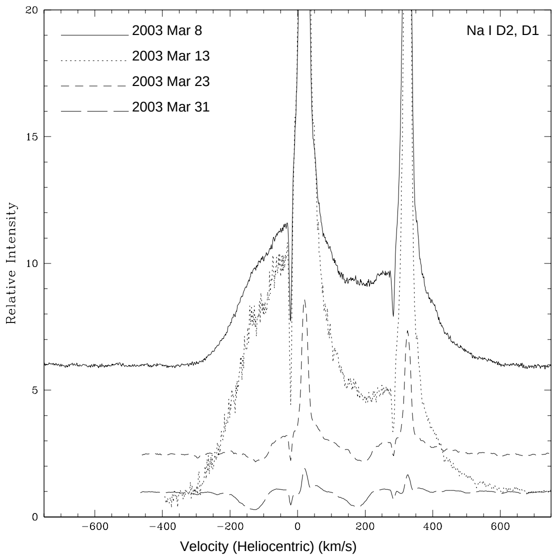

Figure 4. Na D profiles in 2003 March showing the sharp and broad emission components and the development of the high-velocity blue-shifted absorption component.

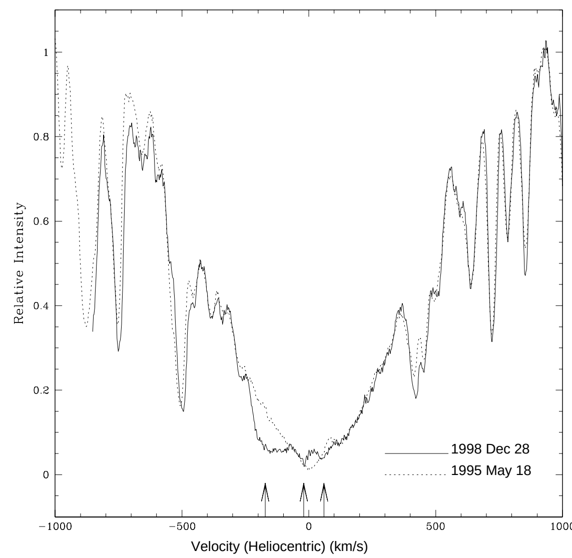

Figure 5. The Ca II H line in 1995 May 18 at maximum light and 1998 December 28 during recovery from minimum light. Note the blue-shifted shell absorption in the H line in the latter spectrum.

blueward reaching a velocity of -132 km s^{-1} on March 31. (This absorption component is also seen in the K I 7664 Å and 7699 Å resonance lines.) The velocities refer to the position of absorption maximum. As in the 1995-1996 and other minima, this absorption appears either soon after minimum light or at the beginning of the recovery to maximum light. At some minima, blue-shifted absorption is also seen in the Ca II H and K lines, as shown in Figure 5 where a spectrum from 1998 December 28 shows clearly the absorption in the H line. The 1998 minimum was shallow, a drop of only 2.5 magnitudes, but of long duration. Our spectrum was obtained 126 days following the initial decline when the star was 1.2 magnitudes below maximum light. This counterpart in the H line to the Na D absorption was not seen in our limited set of 2003 spectra.

There is a distinct difference in the profiles of the broad emission at the two declines (Figure 6). The broad emission of D1 and D2 in the 2003 spectra overlaps in the wavelength interval between the lines. A decomposition of the total emission into two Gaussians is possible. For the 2003 March 8 spectrum, the equivalent widths are 35.7 Å for D2 and 16.9 Å for D1. Their ratio is 2.1 which equals to within the measurement uncertainties the ratio of 2.0 for optically thin lines. The mean (FWHM) width of the Gausssian fits to D1 and D2 is 250 km s^{-1}. The mean radial velocity is 0 ± 7 km s^{-1}. (The profiles of 2003 Na I D broad emission lines are similar to those at the 1989 minimum of R CrB (Lambert, Rao & Giridhar 1990).)

The profiles of D1 and D2 broad emissions at the 1995-1996 minimum are quite different from those observed in 2003. The blended emission between the two lines as well as on the red side of D1 is much more pronounced than in 2003 minimum. While the broad emission in 2003 is well fitted by a single Gaussian, each D line in the 1995-1996 profile requires two Gaussians separated by 213±5 km s^{-1} with the red component stronger than the blue component by about 50 %. The blue component has a larger FWHM (220 km s^{-1}) than the red component (180 km s^{-1}). The mean velocity of the pair of Gaussians is about -2 km s^{-1}. This decomposition of the blended Na D lines into a pair of Gaussians for each line is confirmed by observations in 1995-1996 of the K I resonance lines at 7664 Å and 7699 Å for which self-blending is nonexistent. In contrast to the broad emission He I profiles, the broad emission in the Na D lines is unchanged in radial velocity but changed in profile between 1995-1996 and 2003.

Although the Na D profile changed, the broad emission's flux is similar for the two minima. For the first of the 2003 spectra, the combined flux of D1 and D2 is 1.7 $\pm 0.2 \times 10^{-12}$ erg cm^{-2} s^{-1} . Estimates for 1995-1996 minimum are $1.4 \pm 0.2 \times 10^{-12}$ erg cm^{-2} s^{-1} for 1995 November 2 and $1.6 \pm 0.2 \times 10^{-12}$ erg cm^{-2} s^{-1} for 1996 February 6.

4.1.3 Ca II lines

The Ca^+ ion may be expected to contribute the 3968 Å (H) and 3933 Å (K) resonance lines, the infrared (IR) triplet lines at 8542 Å, 8662 Å and 8498 Å, and the forbidden lines at 7291 Å and 7323 Å. Unfortunately, our HET 2003 spectra do not cover the regions of H and K lines and the infrared triplet lines. The forbidden lines are seen at minimum light spectra as sharp emissions with an equivalent width ratio of 7291 Å to 7323 Åof 2 to 1, as anticipated. A broad component to the forbidden lines with the flux seen at the one magnitude deeper minimum in 1996 would be masked by the brighter continuum of the 2003 minimum.

The H & K, infrared, and forbidden lines were covered in the McDonald spectra obtained in the recovery phase with contrasting profiles (Figure 7). The H & K lines are broad lines without a hint of a sharp emission component but with two (may be even more) sharp absorption features. The IR lines and forbidden lines appear as sharp lines with-

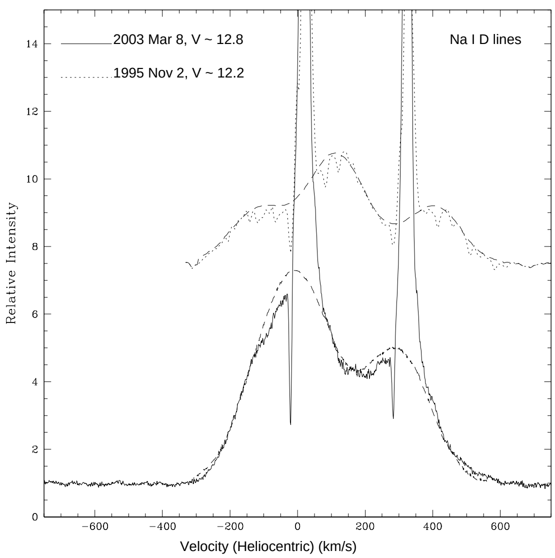

Figure 6. The Na D profiles for 2003 March 8 and 1995 November 2 showing the broad and sharp emission of the D1 and D2 lines. The dashed lines show Gaussian fits to Na D broad emission for 2003 March 8 (one component)and for 1995 November 2 (two components)

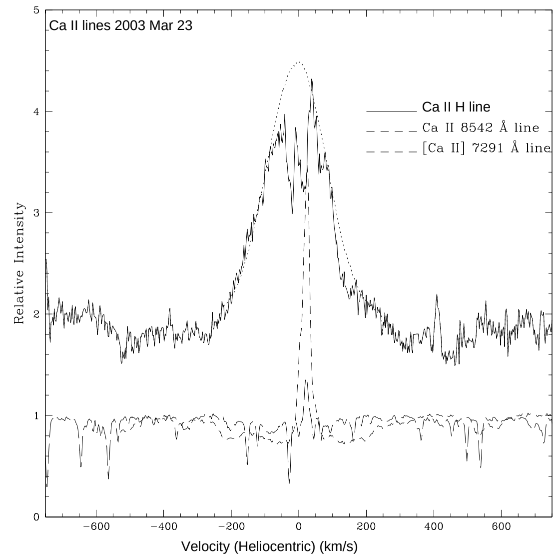

Figure 7. Profiles of three Ca II lines in 2003: the resonance H line, the IR line at 8542 Å, and the [Ca II] line at 7291 Å. Telluric H_2O lines contaminate the region around the [Ca II] line.

out a broad emission component. The absence of the broad emission in the IR lines is consistent with the flux predicted from the branching ratio and the flux in the H & K lines. The broad emission of the H & K lines is fairly well described by a single Gaussian with a mean FWHM of 220 km s^{-1} at a mean velocity of -4 km s^{-1}. These parameters are quite similar to those derived from the Gaussian fit to the Na D lines.

There is a distinct difference in the Ca II H and K broad emission profile in the 2003 and the 1995-1996 declines (Figure 8). The 2003 profile is well fitted by a single Gaussian. The 1995-1996 profiles require two Gaussians with a separation of 181 km s^{-1} and a red Gaussian about 65 % stronger than the blue one. The blue Gaussian has the larger FWHM (204 km s^{-1} to 167 km s^{-1}). The Gaussian fits for Ca II H and K are similar to fits to the Na D lines for the 1995-1996 and the 2003 profiles. These similarities suggest that the emitting regions for the Na atoms and the Ca^+ ions are very closely related, if not identical, both in 1995-1996 and 2003. However, the common emitting regions were differently arranged with respect to the stellar radial velocity at the two minima.

Of interest in the H & K profiles are the absorption features at -21 km s^{-1}, $+16$ km s^{-1}, and $+65$ km s^{-1}, and the absence of a sharp emission component, the analogue of the so prominent sharp emission component to the Na D lines. The -21 km s^{-1} absorption matches the velocity of the narrow Na D absorption seen at maximum light (and in decline) and attributed to interstellar gas (Keenan & Greenstein 1963; Payne-Gaposhkin 1963; Rao & Lambert 1997). The $+65$ km s^{-1} component has no counterpart in other broad emission lines, but variable absorption redshifted relative to the mean stellar velocity is seen in spectra from maximum light (see below). That this redshifted gas is not

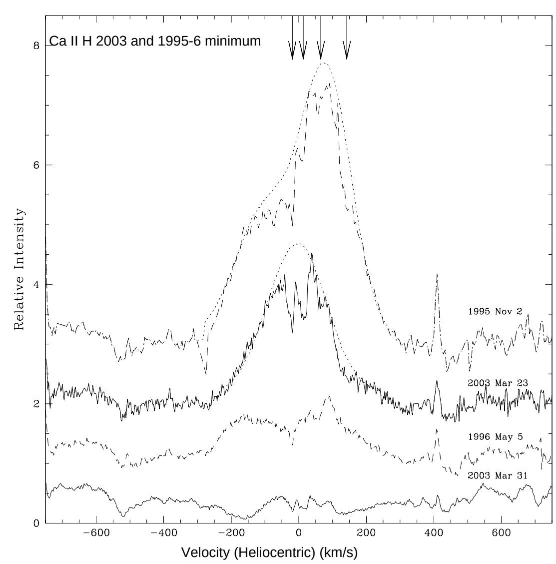

Figure 8. Profiles of Ca II lines H line in 2003 and 1995 minimum. Gaussian fits to the profiles of 2003 March 23 and 1995 November 2 are also shown (dotted lines).The arrows indicate the positions of superposed absorption components.

seen in Na D is probably because Na atoms are singly-ionized in this infalling gas. The $+16$ km s^{-1} component with its blueshift of about 6 km s^{-1} has a velocity similar to that of the sharp IR and the 7291 Å and 7323 Å lines (Figure 7). (The peak sharp absorption velocity in the H & K lines may be shifted to the blue by a few km s^{-1} relative to the IR and forbidden line velocities and the typical ionized 'metal' line.)

Sharp line emission in H & K has been replaced by absorption. If the sharp line region were optically thin to the Ca II lines, the flux in the H & K sharp lines estmated from the branching ratio and the flux in the IR lines would be several times the actual flux in the broad H and K lines, but observations show, as in 1995-1996, that the sharp emission lines are absent. Absorption seen as several apparently discrete components is in part presumably due to optically thick gas projected in front of part or all of the broad line emitting region.

A likely principal reason for the absence of the sharp lines is that the emitting layers are optically thick to the resonance lines, as suggested by the following argument. If the IR triplet lines are optically thin, the intensity ratios expected for 8498 Å : 8542 Å : 8662 Å are 1:9:5. Observations at the 1995-1996 minimum show roughly equal fluxes for the three lines, i.e., the emitting gas is not optically thin. The optical depth in the H & K lines has certainly to be several times higher than in the IR lines. The observed flux ratio of the [Ca II] lines to the IR triplet lines is estimated to be 0.03. The calculations of Ferland and Persson (1989) suggest that for an electron temperature of T_e between 3000 to 10000 K that the observed flux ratio of forbidden to IR triplet lines is found for electron densities of $N_e \sim 10^{10\pm1}$ cm^{-3}, a value consistent with other estimates for the 1995-1996 minimum (Rao et al. 1999). Their calculations indicate that the observed fluxes and the inferred electron densities imply optical depths in the H & K lines of $\tau \sim 10^4$. Thus, we suppose that suppression of sharp emission in the resonance lines is possible.

4.1.4 [N II] lines

The [N II] line at 6583 Å is weakly present in 2003. The maximum intensity is about 10% of the local continuum in the 2003 March 8 and 13 spectra. (The weaker 6548 Å and 5754 Å lines are not detected.) The profile appears to be very similar to the well determined profile from the 1995-1996 minimum: broad with a central minimum between two peaks of equal intensity. This profile differs from that presented by other broad emission lines. With the accurate rest wavelength (6583.454 Å) determined by Spyromilio (1995) and Dopita & Hua (1997), the centre of the line in 2003 is at a velocity of -6 ± 4 km s^{-1}. The velocity range at the base extends from -163 to 140 km s^{-1}. The flux in the line is about $1.2\pm0.2 \times 10^{-14}$ erg cm^{-2} s^{-1} on 2003 March 8 and 13 whereas the flux on 1996 February 6 is $1.7\pm0.2 \times 10^{-14}$ erg cm^{-2} s^{-1}. Differences in profile and flux betweem 1996 and 2003 are not be significant.

4.2 The Sharp emission lines

Available data suggest that sharp emission lines of abundant singly-ionized and neutral metals, are seen in all declines of all RCBs from soon after onset of a decline through minimum light to near full recovery to maximum light. The lines generally show a slight blueshift with respect to the mean velocity of the star as measured from absorption lines at maximum light. First, we comment on these sharp lines as seen in the 2003 spectra and then report on a first for R CrB - sharp emission lines of the C_2 molecule.

4.2.1 Sharp emission lines – atoms

Our 2003 spectra are rich in sharp emission lines of Sc II, Ti II, Fe I, Fe II, Y II, Ba II and other species with a level of excitation similar to that in 1995-1996. The lines in 2003 are broader (FWHM $\simeq$ 20 km s^{-1}) than in 1995-1996 (FWHM $\simeq$ 15 km s^{-1}). Radial velocities of these lines are shown in Table 2. It will be seen that the blueshift relative to the mean stellar velocity at maximum light of +22.5 km s^{-1} is absent or very small for our 2003 spectra. Except for a suggestion that the velocity may have been slightly different on 2003 March 8, the sharp lines do not show a velocity variation over this interval of less than a month. This lack of a velocity variation is consistent with a near-constant velocity for these lines over the entire duration of the 1995-1996 minimum.

The sharp emission lines in the 1995-1996 spectra often but not always showed velocity structure suggestive of a blend of two or three components. In 2003, the line profiles arise from a single component with a velocity equal to that of the strongest component seen in 1995-1996. Such profiles were seen on occasion in 1995-1996. The mean level of excitation decreased between March 8 and March 13; the Fe II lines weakened and Fe I lines got stronger relative to the continuum. which, as judged by the V magnitude, was approximately constant in this six day period.

A few forbidden transitions are seen as sharp emission lines: [Ca II] at 7291 Å and 7323 Å, [O I] at 6300 Å, and [Fe II] at 7155 Å in the spectral region covered in the HET spectra at minimum. The [Ca II] lines were also present in the spectra obtained later in March on the recovery from minimum. The [C I] 9850 Å line is present in the spectrum of March 23.

The emission lines in 2003 are of higher relative intensity at a given V magnitude than in 1995-96 minimum. Figure 9 shows the spectrum in the region of the Si II 6371 Å line. The 2003 March 8 spectrum (V = 12.8) is compared with 1995 November 2 (V =12.2) on the descent to light minimum and at light minimum on 1996 February 6 (V=13.5) when the lines are in absorption. Comparison of spectra at the same V magnitude during the recovery to maximum light from the minimum gives the same result – see the spectra of 2003 March 23 and 1996 May 5 in Figures 9 and 10. These differences are not unexpected because our coverage of the sharp lines through 1995-1996 minimum showed that a line's flux changed, presumably due to varying obscuration of the emission region by dust.

4.2.2 Sharp emission lines - the C_2 molecule

The 2003 minimum spectra for March 8 and 13 show C_2 Swan bands in emission. The observed spectral region included the 1-2, 0-2, and 1-3 bands. The rotational structure is well resolved but at the 1995-1996 minimum the lines were so broadened that rotational structure was not resolved (Rao et al. 1999). Such a change from sharp to broad Swan lines has been seen previously in V854 Cen: the 1998 minimum of V854 Cen showed sharp Swan lines but the lines were broad at the 1992 minimum (Rao & Lambert 2000).

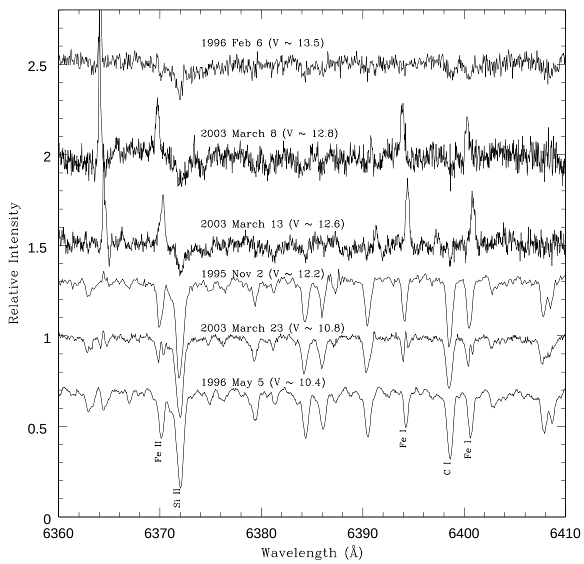

Figure 9. Sharp emission lines in the 6370 Å region in the 1995-1996 and 2003 minima.

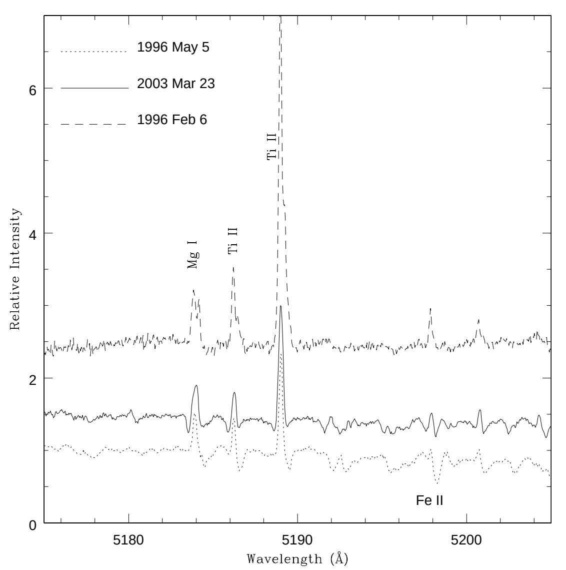

Figure 10. Sharp emission lines near 5190 Å at the 1995-1996 and 2003 minima.

4.2.3 C I emission lines

A characteristic of the sharp 'metal' lines is the near constancy of their velocity (and profiles) during the decline and recovery from minimum light. The C I emission lines in contrast appear with a variable velocity. The lines were in emission on 2003 March 8 (Figure 11) with a velocity of 15 km s^{-1}. The emission moved redward achieving a velocity of 37 km s^{-1} on March 13. The observation that the velocity of the C I emission migrates from 13 to 37 km s^{-1} but the low excitation sharp metal emissions are stationary suggests a distinctly different character to the high excitation emissions.

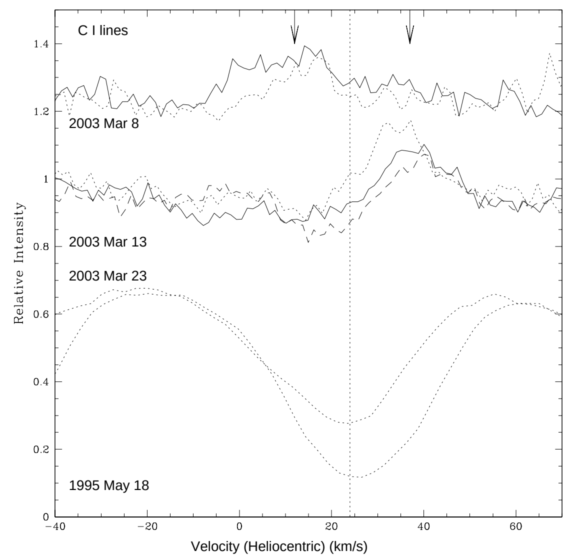

Figure 11. Emission in the C I lines at 7111, 7113, and 7115 Å lines at the 2003 minimum. The velocity scale is set for the 7113 Å line with the vertical line representing the average heliocentric velocity of the star at maximum light. The solid line shows the 7113 Å emission profile for 2003 March 8 (top) and 2003 March 13 (middle) and the absorption profile for 2003 March 23. The dotted line (top and middle) shows the 7111 Å profile and the dashed line (middle) shows the 7115 Å profile for the same velocity zero point as the 7113 Å line. Emission on March 8 is centred at +13 km s^{-1} and on March 13 at +37 km s^{-1} (see arrows at the top of the figure).

In the spectra obtained after March 8, the C I lines are in absorption but weaker than at maximum light with an apparent filling in by emission. For example, the 6828 Å line not only shows movement of the emission peak from blue to red from 2003 March 8 to 13, but also shows variable emission in the absorption core between 2003 March 13 and March 31 with a tendency to oscillate between a velocity of about +11 and +30 km s^{-1} (Figure 12).

Pure emission at minimum light, as in Figure 11 and 12, was not seen in the 1995-1996 but our sampling then was less than optimal; minimum light coincided with R CrB's passage behind the Sun and on its emergence, when the star was recovering to maximum, our data were sparsely spaced in time. Nonetheless, the C I profiles were variable to a similar extent and on a comparable timescale in 1995-1996 and 2003. This is shown by Figure 13. High excitation lines of other atoms show similar short period changes in their line profiles.

This transient emission in C I and other lines in the 1995-1996 minimum was interpreted as a signature of shock propagation related to the photospheric pulsation (Rao et al. 1999), as suggested in the model proposed by Woitke et al. (1996). The repeated occurrence of C I emission migrating from blue to red in a period of about 5 days suggests such a propagating pulsation-related shock with molecules forming in cooled gas behind the shock (Woitke et al. 1996). The shock cannot be a normal feature of the photosphere because the C I emission, if seen without obscuration by dust, would be very intense and a strking feature at maximum light,

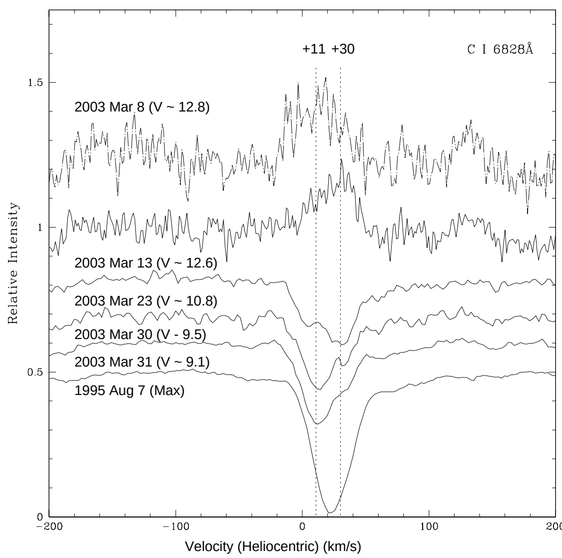

Figure 12. Profiles of the C I 6828 Å line on 2003 March 8, 13, 23, 30, and 31 along with the profile at maximum light from 1995 August 7. The V magnitudes of R CrB at the time of observation are given on the figure.

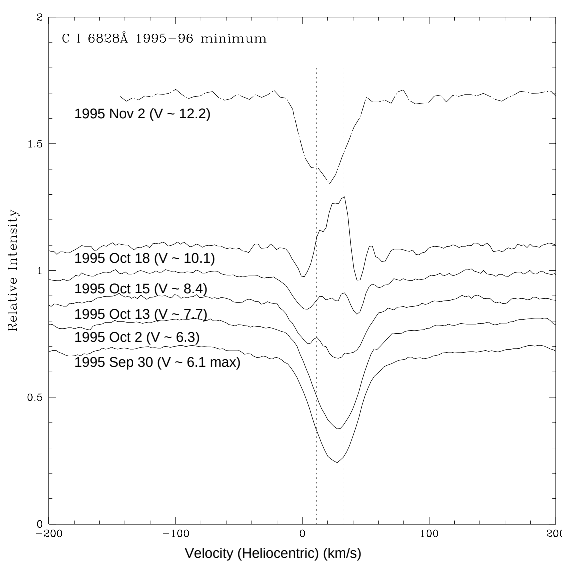

Figure 13. Profiles of the C I 6828 Å line on 1995 September 30, October 2, 13, 15, 18, and November 2. The V magnitudes of R CrB at the time of the observations are given on the figure. The vertical dashed lines indicate radial velocities of 11 and 31 km s^{-1}.

but all of our spectra taken at maximum light show pure absorption profiles with no hint of overlying emission. The emission may come from a disturbed photospheric region associated with the region of dust production. More likely, the emission may be produced above the photosphere where a shock also leads to dust.

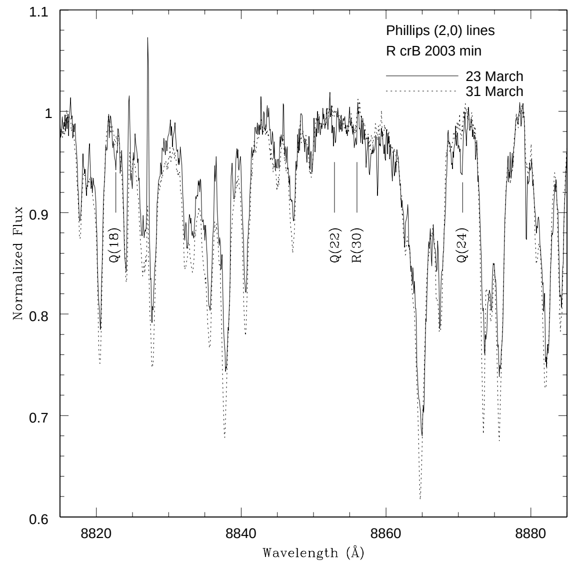

Figure 14. Sharp absorption lines of the C_2 Phillips (2-0) band on 2003 March 23. The C_2 lines are not present in the 2003 March 31 spectrum.

5 ABSORPTION LINES OF THE C_2 PHILLIPS SYSTEM

One supposes that dust formation is preceded and accompanied by molecule formation. The C_2 molecule is expected to be an abundant molecule, and, as noted above, sharp emission from these molecules is seen in the Swan bands. The lower level of these bands is not the molecule's ground state but connected to it by a forbidden transition. C_2 absorption may more likely to be detected using the Phillips system, an electronic transition from the ground state. Absorption in the Phillips bands was previously seen in V854 Cen during its 1998 minimum (Rao & Lambert 2000).

Examination of our 2003 March 23, 30, and 31 spectra of R CrB showed the presence of weak absorption lines corresponding to the lines of the 2-0 Phillips band (Figure 14) in the March 23 but not the March 30 and 31 spectra. The HET spectra obtained earlier during the minimum did not cover the spectral region of either the 2-0 or the 3-0 Phillips bands. The C_2 Phillips lines were not seen in absorption (or emission) in the 1995-1996 minimum for which our spectral coverage was extensive. This absence of the Phillips lines is very likely explained by the fact that C_2 Swan emission lines in 1995-1996 were broad and thus one may suppose that attendant absorption lines would also have been broad and so undetectable.

A Boltzmann plot constructed from the equivalent widths of seven 2-0 lines suggests a rotational excitation temperature of $T_{rot} = 1377 \pm 150$ K (Figure 15), assuming the lines are unsaturated. The mean radial velocity of the lines is +10 km s^{-1} equivalent to a blue shift of 13 km s^{-1} with respect to the photosphere. For comparison, we note the excitation temperature for the C_2 molecules at the 1998 minimum of V854 Cen was 1100 K.

The C_2 molecules are likely to reside close to the freshly formed dust, probably below the dust cloud. On March 23

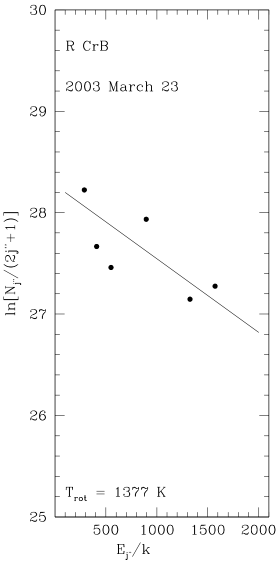

Figure 15. Boltzmann plot for the C_2 Phillips 2-0 absorption lines from the 2003 March 23 spectrum.

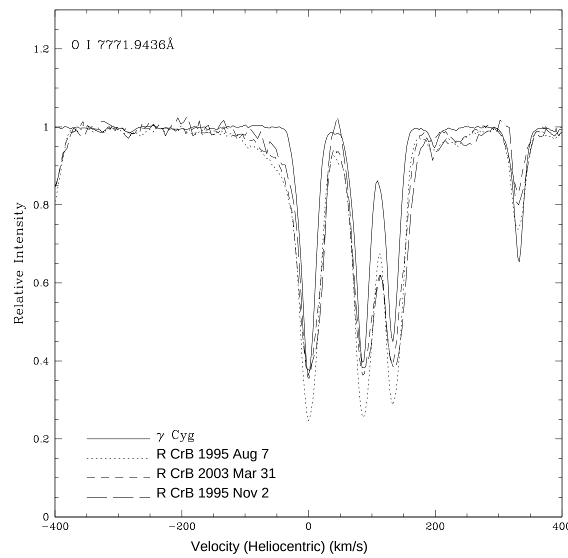

Figure 16. Profiles of the O I 7772 Å triplet on 2003 March 23 and 31 and at maximum light on 1995 August 7 compared with the profile in γ Cyg. The zero point of the velocity scale is set for the bluemost line of the triplet.

when the sharp Phillips lines were detected in absorption, the dust cloud was not providing veiling of the photospheric lines (Figure 9). Detections of C_2 Swan bands in emission on March 8 and 13 were made when veiling of photospheric lines was evident (Figure 9) yet the C_2 lines were sharp. Then, the C_2 molecules can not have been viewed through the parts of the dust cloud projected on to the photosphere. The line of sight to the molecules must have been dust free or relatively so.

6 VEILING OF THE PHOTOSPHERIC LINES

The spectra of 2003 March 8 and 13 are almost completely devoid of absorption lines, even the strongest lines such as the Si II 6347 Å and 6371 Å lines (Figure 9) are greatly weakened and possibly broadened. By March 23 when our next spectrum was obtained, the absorption spectrum had largely returned to its appearance at maximum light. A similar behaviour of absorption lines was extensively described for the 1995-1996 minimum by Rao et al. (1999). Figure 9 shows three spectra from that minimum including the one for 1996 February 6. Scattering of photospheric light passing through the dust cloud Doppler-broadens the light and washes out the absorption lines.

7 AN INDICATOR OF A STELLAR WIND

The spectrum of R CrB is so rich in novelties that some may be missed by even serious inspection. In examining the new spectra, we noticed that the O I triplet lines at 7771-5 Å show extended blue wings on the profiles obtained on 2003 March 23, 30, and 31 (Figure 16). This extension is clearly revealed by comparison of the blue wing of the 7772 Å line and the red wing of the 7775 Å line and by contrast with the O I profiles for γ Cyg where the lines are of a similar strength. The extended blue wing is seen in hindsight on all spectra taken with R CrB at maximum light as well as those from the 1995-1996 decline. The wings extending to velocities of about -130 km s^{-1} from line centre are suggestive of a strong wind. A wind velocity of over 130 km s^{-1} exceeds the predicted escape velocity of 30–70 km s^{-1} (Rao & Lambert 1997).

A wind was previously suggested by observations of the He I 10830 Å line at maximum light showing blueshifted absorption at a velocity of about 200 km s^{-1} in spectra acquired at or near maximum and spanning more than two decades (Querci & Querci 1978; Zirin 1982; Clayton, Geballe & Bianchi 2003). Some spectra have shown also redshifted emission suggesting a P Cygni-like profile. A point for He I is added to Figure 16.

Strength of the wind as seen in O I appears to be nearly constant and little, if at all, changed from maximum to the faintest magnitudes at which the absorption spectrum is unaffected by veiling. Figure 17 shows seven spectra from 1995 May 18 to 1995 September 30 in which six show essentially identical profiles with extended blue wings. The seventh spectrum taken on 1995 September 30 was taken one day prior to the onset of the 1995-1996 decline and its more extended blue wing may have been a harbinger of the decline.

In contrast to the O I profiles, there is appreciable variation in the blue wing of the Al I 3944 Å resonance line. (Similar variations are present in the Na D lines (Rao & Lambert 1997 and Figure 19) but their definition is compromised by the presence of the blue-shifted interstellar Na D lines and telluric H_2O lines.) Figure 17 shows the spectrum around the Al I line for the same dates between 1995 May and September. Large variations in the absorption to the blue of the photospheric Al I line are seen. Several spectra show a 'cloud' at -40 km s^{-1}. Others show an extended blue wing out to about -50 km s^{-1}. These variations on

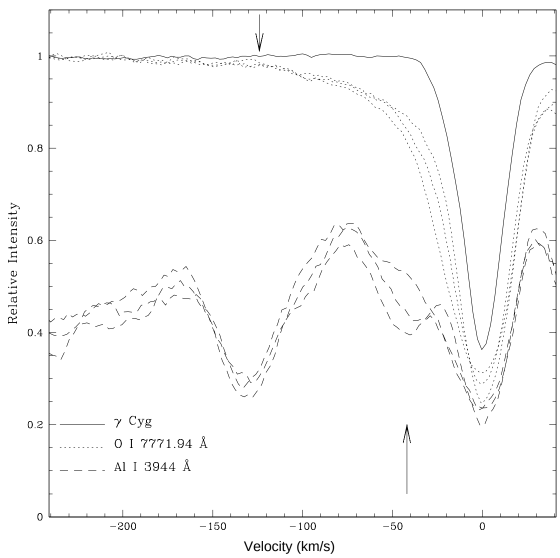

Figure 17. Seven spectra of the O I 7772 Å (top) and the Al I 3944 Å line of R CrB at maximum light from 1995 May 18 and September 30. The O I line from γ Cyg is shown (solid line). The velocity zero point is set at the centres of the O I and Al I lines.

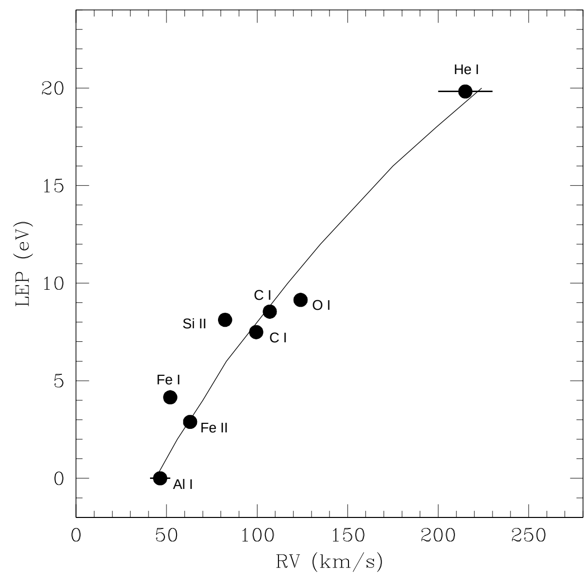

Figure 18. Wind velocity versus lower excitation potential of the line for spectra at maximum light from 1995 May to September. The data point for He I is from Clayton et al. (2003).

the Al I profile stand in stark contrast to the lack of profile variations in the photospheric line shown at -130 km s^{-1}.

Inspection of spectra show that the inferred wind velocity decreases with excitation potential of the line: Si II at 6347 Å and 8.3 eV shows 82 km s^{-1}, C I at 6828 Å and 8.5 eV shows 107 km s^{-1}, and 9112 Å and 7.5 eV shows 100 km s^{-1}, Fe II at 6369 Å and 2.9 eV shows 63 km s^{-1} , Fe I at 7511 Å and 4.1 e.v shows 52 km s^{-1}, and Al I (and Na I D lines) of 0.0 e.v showing 44 km s^{-1}. Clayton, Geballe & Bianchi's (2003) reported wind velocities of 200 to 240 km s^{-1} at maximum from the He I 10830 Å line, apparently extend the velocity - excitation relation shown in Figure 18. In addition to the outflowing gas comprising the stellar wind, there is evidence for infalling gas of variable strength at maximum light, as revealed by the Ca II H & K and IR lines (Figures 19 and 20). This gas is not seen in the Na D lines; the red wing of the Na D lines is unchanged during the Ca II variations (Figure 19).

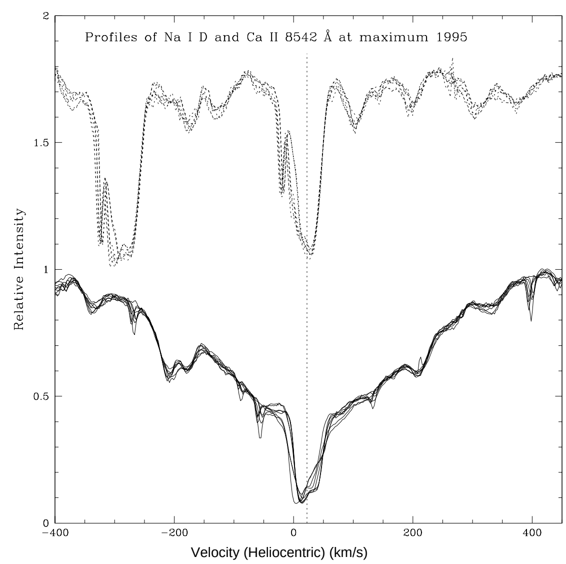

Figure 19. Presence of stellar wind in Na I D (top) and Ca II 8542 Å (bottom) lines from spectra at maximum light from 1995 May to September. Note the absence of redward extensions in Na I D lines where as Ca II 8542 Å line shows both red and blue extensions to the profile (variable). The vertical dashed line refers to the average radial velocity of the star. The profiles are normalised to the stellar velocity.

8 DISCUSSION

Even a qualitative interpretation of the spectrum of R CrB in decline must today be circumscribed with qualifications and admissions of ignorance. Our comparison of spectra from the 1995-1996 and 2003 declines adds new information whose full significance may become clearer with observations from future declines of R CrB. Here, we restrict comments to general features of the absorption and emission spectrum of the star.

Our discovery of extended blue wings to strong lines observed at maximum light suggests the presence of a permanent wind off the surface of R CrB (and the other RCBs for which we have suitable spectra). The wind velocity increases with a line's excitation potential. Variable non-photospheric Doppler-shifted absorption is seen in several resonance lines: blueshifted absorption in Na D and Al I and blueshifted and redshifted absorption in the Ca II H & K and IR lines. These variable components which suggest a circulation of gas may be linked to the photospheric pulsations.

Evidence for a wind off R CrB and other RCBs was earlier provided by Clayton et al. (2003) from observations of

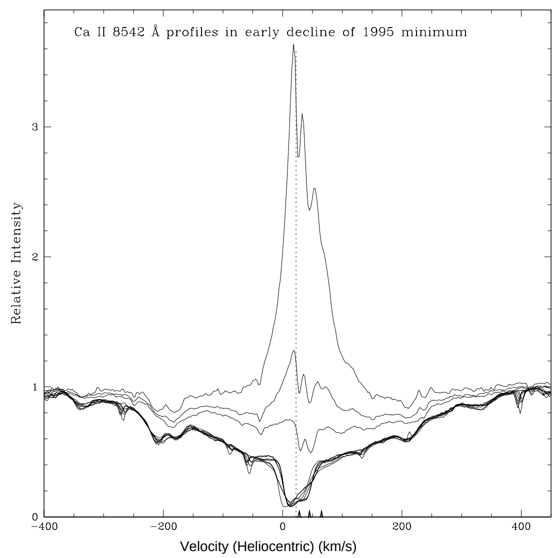

Figure 20. Ca II 8542 Å line during early decline of 1995-1996 minimum. The lowest set of profile refer to maximum light The upper profiles show the change the minimum progress from 6 to 10.2 magnitude. Note the presence of redward superposed absorption components at +28, +45 and +66 km s^{-1}. The vertical dashed line refers to the average radial velocity of the star of 22.5 km s^{-1}.

the He I 10830 Å line showing blue-shifted absorption with or without accompanying emission. Clayton et al,'s modelling of the profiles suggested that the line is formed by collisional excitation and that acceleration of the wind to its possibly terminal velocity (indicated by the 10830 Å profile) is steep. Such conditions in the wind are likely conducive to the absorption of O I 7772 Å by the wind. The base of the wind must cover large fractions of the photospheric area in order that the blue wing of a strong line vary little, if at all, at maximum light.

One interpretation of the extended blue wings is that the wind begins at the top of the photosphere and increases in velocity and excitation with height above its base. Heating of the wind may be by deposition of mechanical energy (sound and/or hydromagnetic waves); the photospheric absorption lines have a width indicating mass motions with a velocity exceeding the local sound speed of about 5 km s^{-1} (Rao & Lambert 1997).

A decline occurs when a soot cloud begins to form along the line of sight to the star. The trigger for dust formation may be a pulsation-induced outwardly propagating shock (Woitke et al. 1996). Calculations indicate that temperatures behind a shock can drop to below 1500 K at densities sufficiently high for carbon atoms to stick to provide an obscuring layer of soot. The shock and soot may initially form over a small part of the visible photosphere but lateral expansion of the soot cloud will result in obscuration of the entire earth facing hemisphere of the photosphere. As soot forms and spreads, the sharp emission lines are revealed. While the cloud may be a local phenomenon, the regions emitting the sharp lines would appear to be more widespread both in terms of spatial coverage and in height above the photosphere (Rao et al. 1999). The intensity of the sharp lines in contrast to the intensities of the broad lines clearly declines with increasing obscuration of the star; The broad line region must be even more extended than the sharpline region. When the photospheric absorption lines are 'veiled' by a thick cloud of soot, the sharp lines, although diminished in flux, remain sharp. Therefore, the region emitting the lines extends off the photosphere and beyond the boundaries of the soot cloud.[§]

The several types of broad emission lines present interpretative challenges. The He I lines with their quasi-parabolic profiles and a mean variable velocity close to the photospheric mean velocity may be associated with the wind: the velocity offsets relative to the mean velocity was -60 km s^{-1} in 2003 and -30 km s^{-1} in 1995-1996. If the emitting region of the wind has a radius at least a few times the stellar radius and is approximately uniform – back and front, the broad line will have a rather smooth profile centred on the mean stellar velocity with a width that is about twice the wind's velocity for the helium emitting layers. The lines' blueshifts may result from occultation of the receding wind behind the star. Weak redshifted emission also suggests that occultation is occurring. Assuming that the velocity of the blueshifted absorption in the He I 10830 Å line reported by Clayton et al. (2003) is representative of the He emitting region, the observed FWHM of our He I lines is accounted for in a qualitative sense. Departures from a smoothly distributed wind or variations in helium line excitation will result in profile variations.[¶]

The broad emission profiles of the Na D and Ca II H and K lines are similar for a particular decline but this profile in 1995-1996 differed clearly from that in 2003: a single Gaussian fits the 2003 profile but two well-separated Gaussians are required to fit the 1995-1996 profiles. Yet, the mean velocity of the broad emission at both declines was similar and close to the mean stellar velocity. Additionally, the line fluxes appear to be little changed during and between declines suggesting that the bulk of the emitting region is unobscured by the fresh soot cloud.[‖]

In contrast to the broad helium emission lines, the velocity width of the Na and Ca$^+$ emission is much greater than wind velocity of Na and Ca$^+$ atoms, as indicated by the blue extensions to the wings of the photospheric Na D and Ca H & K absorption lines. Although the 2003 Na D and Ca H & profiles are similar to those of the helium emission

§ Rao, Reddy & Lambert (2004) speculated that RCBs may posses a dusty equatorial torus and polar winds. The polar winds provided the sharp emission lines from heights relatively close to the star. The sharp line's velocity (relative to the mean stellar velocity) depends on the circulation of the polar axis and the extant to which the fresh cloud blocks the approaching and receding polar winds.

¶ One expects a drift velocity between dust grains and gas atoms. This velocity offers the potential for either collisions between dust grains and helium atoms or collisions between helium atoms and electrons reflected off grains to lead to excitation of helium atoms and helium line emission.

‖ The Na D broad emission from V854 Cen in a deep decline was unpolarized when the continuum was polarized showing that the emission in that case was also unobscured by the dust cloud responsible for that decline (Whitney et al. 1992).

(suggesting a common origin for He, Na, and Ca lines in the outer reaches of the wind), colocation of He and Na atoms and Ca^+ ions is not supported by the profiles in 1995-1996 of Na D and Ca H & K lines which differed dramatically from the the He I emission profiles: the Na D and Ca H & K lines appeared as two well separated Gaussians but the He lines were fit by a single Gaussian. Although the Na D and Ca H & K profiles changed so greatly between the two declines, the central emission velocity was unchanged and at a value only slightly blueshifted from the mean stellar velocity. Apparently, the emitting Na atoms and Ca^+ ions were approximately symmetrically distributed about the star but with different distributions on the two occasions; perhaps, for example, the emitting gas is in a variable with polar symmetry. Perhaps also, the dissimilar but symmetric distributions from 1995-1996 and 2003 are merely fortuitous and future observations of the Na D and Ca H & K lines will show a wide variety of profiles with mean velocities differing appreciably from the mean stellar velocity. Then, firmer clues to the geometry of the broad emission line regions should be provided.

Indeed, the unresolved key questions about the various emission and absorption features seen at minimum light may be thought to concern the geometry of R CrB's outer atmosphere. To conclude, we list the questions and comment very briefly on some geometric questions.

Does the wind have a latitude dependence? Is this variation slight or extreme? We noted above our earlier suggestion that the wind off a RCB may be stronger over the poles? Are the He I broad emissions lines good tracers of the high-velocity wind? Are the Na D and Ca II H and K broad emission lines related to the wind?

Are there preferred stellar latitudes for formation of dust clouds? If so, one supposes that dust clouds and their accompanying gas reside in a torus about the star. Evidence for asymmetrical distributions of dust about RCBs has been discussed previously (see, for example, Clayton 1996; Rao et al. 1999) If there is a torus, which broad (presumably) emission lines arise there? One may suspect that dust formation may be inhibited at locations from which a fast wind originates. Thus, a dust torus and polar winds may be a natural pairing.

An extended region seems demanded to account for the sharp emission lines. Is this region restricted to cetain latitudes and locations?

These questions of geometry must be paired with corresponding questions about the excitation of the lines which lead into further questions about the heating and cooling of the gas and dust. All of these and the above questions may be answered by additional observations of RCBs in decline. This paper certainly helps to suggest which spectroscopic signatures may be unchanged or little changed and which can be appreciably changed from one decline to another decline of R CrB. To define the full range of decline to decline differences (or the lack thereof) across a sample of RCBs will be a herculean task.

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