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# High Resolution Spectroscopy of R Coronae Borealis during the 1988–1989 Minimum

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**Abstract.** Moderate-resolution spectra of the $C_2$ Swan 0–1 bandhead, the Na I D lines and the K I resonance lines near 7660 Å obtained at minimum light during the 1988–1989 decline of R CrB are discussed and interpreted in terms of a popular model for R CrB declines. High-resolution spectra obtained at maximum light show blue-shifted chromospheric emission in the cores of the Na I D and the Sc II 4246.8 Å lines.

*Key words*: spectroscopy, R CrB — 1988-1989 minimum

## 1. Introduction

The class of R Coronae Borealis stars (RCBs) must be among the least well understood peculiar stars. Chief among the puzzling characteristics of RCBs is the origin of the irregularly occurring deep minima. As RCBs in decline are observed spectroscopically with contemporary telescope and instrumentation, one may suppose that novel insights will be gained into the origin of the mysterious declines and the ensuing changes in the atmospheric structure. In this paper, we present and discuss high-resolution high signal-to-noise ratio spectra in intervals containing the $C_2$ Swan 0–1 bandhead at 5634 Å, the Na I D lines at 5890 and 5896 Å, and the K I resonance lines at 7663 and 7699 Å. The spectra were obtained during the minimum of R Coronae Borealis (R CrB) that began in 1988 July in which the star faded to $m_v \sim 11$ by 1988 September with a recovery to maximum light ($m_v = 5.8$) achieved by the spring of 1989. We observed R CrB twice at minimum in 1988 September–October and again in 1989 February when at $m_v \simeq 7.5$, the star was rising to maximum brightness. In 1990 January, we observed the Na I D lines when R CrB was at maximum. High resolution observations at maximum light were acquired of selected lines to search for chromospheric emission.

Several discussions of spectroscopic monitoring of R CrB through earlier declines have been given in the literature: *e.g.*, Herbig (1949), Payne-Gaposchkin (1963), Rao (1974), and Holm *et al.* (1987). The 1988-1989 minimum was observed intensively by Cottrell, Lawson & Buchhorn (1990, hereafter CLB) in selected spectral intervals at moderate resolution and signal-to-noise ratio. Key spectroscopic signatures of R CrB in decline were noted first by Joy & Humason (1923). These signatures are not peculiar to R CrB for they recur in the extensive spectroscopic (and photometric) study of RY

Sgr conducted by Alexander *et al.* (1972) between 1967 and 1970 including the very deep minimum of 1967-1968 when RY Sgr faded by about 8 mag (see also Spite & Spite 1979).

Specific signatures denote the decline, the minimum, and the recovery to maximum light of an RCB star. Herbig (1949) noted that spectrograms at 75 Å mm $^{-1}$ taken as R CrB faded to $m_V \sim 10$ "showed no perceptible change in the absorption spectrum" relative to spectra taken at maximum light. In the 1948-1949 minimum discussed by Herbig, R CrB faded to a visual magnitude of 14, or 2 to 3 magnitudes below the 1988-1989 minimum. At $m_V \sim 10$, sharp emission lines appeared in the spectrum. In the 1988 decline, CLB's spectra at 0.5 Å resolution and low S/N show sharp emission lines appearing at $m_V$ ~7.7. CLB assert that photospheric absorption lines, even the $C_I$ high-excitation lines, are filled in by emission very early in the decline; their notes indicate this to occur at $m_V \sim 6.6$ or less than a magnitude below the maximum. The emission lines are generally attributed to an extensive chromosphere that IUE observations of the emission lines Mg II 2800 Å and C II] 1335 Å at maximum light show to be most probably a permanent feature of R CrB (Rao, Nandy & Bappu 1981; Holm & Wu 1982). An outstanding characteristic of the sharp emission lines is that, in the decline from maximum light, they are blue-shifted by 10 to 15 k m s $^{-1}$ with respect to the photospheric velocity at maximum light. This velocity difference, which was noted first by Joy & Humason (1923), has been reported for all well-observed minima including that of 1988-1989 (CLB). Additional emission features include the CN violet system band near 3883 Å (Herbig 1949,1968), the $C_2$ Swan bands (Payne-Gaposchkin 1963), and the [O II] doublet discovered by Herbig (1949). Quantitative spectroscopy of these features has not been reported.

A distinctive set of emission lines is seen at faint magnitudes. Broad (FWHM ~ 200 km s $^{-1}$) emission lines of He I 3889 Å, $Ca_{II}$ H and K, and $Na_I$ D lines are seen with approximately parabolic profiles (Rao 1981). These lines, which are unshifted with respect to the photospheric velocity, are sometimes accompanied by blue-shifted absorption at a velocity of 100 to 200 km s $^{-1}$ . These emission lines, which were seen first by Joy & Humason (1923) and have been seen at subsequent faint minima of R CrB, have been seen also in RY Sgr at minimum (Alexander *et al.* 1972; Spite & Spite 1979). Even the cool R CrB star U Aqr at minimum shows the broad line at 3889 Å, which is even stronger than the Ca II H and K lines (Bond, Luck & Newman 1979). It is usually supposed (*e.g.*, Feast 1986) that these lines arise from the expanding circumstellar shell.

The photospheric spectrum has been reported to change character at minimum light Herbig (1949) refers to the spectrum as "heavily veiled ", *i.e.*, the lines appear diluted or, perhaps, broadened by a continuous spectrum. Payne-Gaposchkin (1963) refers to the "absorption spectrum, whose line profiles undergo distortion or doubling at times". Herbig noted the onset of veiling to occur at $m_V \sim 10.8$ in the decline. Payne-Gaposchkin(1963)reports that veiling first occurred in the 1960 minimum at $m_V$ ~10.5 following the initial minimum at $m_V \sim 11.0$ that occurred 50 days earlier with only minor increases in brightness separating the minima. This veiling appears to differ from the weakening and disappearance of lines that occurs with the emergence of the chromospheric lines. The veiled absorption spectrum seems to be that of the normal photosphere, but quantitative descriptions have never been given.

In the following sections, we present and discuss high-resolution spectra in the context of the principal spectroscopic signatures and a popular phenomenological model of the declines that are a unique characteristic of the RCBs.

## 2. Observations

R Coronae Borealis was observed at the W. J. McDonald Observatory in 1988 September-October when the star was at minimum light (V ~ 10–10.5) following the onset of the decline in early July. Three spectral regions, each about 50 Å wide and at a spectral resolution of 0.2 Å were observed with the coudé spectrometer of the 2.7 m reflector (see Table 1). The detector was a Texas instruments CCD. Since telluric lines contaminate the exposures at 5880 and 7681 Å, a hot rapidly rotating star was observed at these wavelengths and at an airmass similar to that at which R CrB was observed. Then, the ratio of the R CrB spectrum to that of the hot star is almost devoid of telluric lines. The trio of spectra were acquired again in 1989 Feburary when R CrB was at $m_v$ ~ 7.5. The interval at 5880 Å including the Na I D lines was observed in 1990 January when R CrB was at maximum light. Spectra of selected lines were obtained in 1990 at a resolving power $\lambda/\Delta\lambda$ ~100,000. In this paper, we discuss high-resolution spectra of the Na I D lines and the strong Sc II line at 4246.8 Å.

*The Na I D lines.* Emissioninthe Na I D lines is the outstanding feature of the two spectra taken when R CrB was at minimum (Fig. 1). The absorption lines of He I at 5876 Å, C I and FeI at minimum have profiles similar, but not identical, in strength and shape to those in the spectra taken on the rise to maximum and at maximum. This similarity is shown in Fig. 2 where the illustrated spectra are those obtained by subtracting the spectrum at maximum light from those obtained in the 1988-1989 decline. We refer to these spectra obtained by the subtraction as “differenced” spectra; the continuum of a differenced spectrum is set at unity. The only strong features in the differenced spectra at minimum light are the Na I D lines with their complex profiles. Small residuals appearing at the positions of the photospheric lines are probably due to slight changes in the strength and shape of the photospheric lines. These changes may be unrelated to the occurrence of the deep minimum and may be due to the pulsation of the envelope. Our spectra certainly show that “veiling” did not occur. Veiling at the 1949 and 1960 minima was reported when the star was fainter than the limit reached in this minimum. In order to interpret correctly such small changes of the photospheric lines, it will be necessary to determine the instrumental profile and to

**Table 1.** Radial velocities (km s$^{-1}$) during the 1988–1989 decline.

| | | λ(Å) | C I | Fe I | Others | Na I[a] |
|---|---|---|---|---|---|---|
| 1988 | Sep 30 | 5880 | 23.6 (3)[b] | 18.1 ± 2 (6) | 20.3 (3) | 21[c] <br> −115[d] |
| | Oct 1 | 7681 | 22.9 (4) | 21.9 (1) | 21.5 (4) | |
| | Oct 2 | 5616 | 22.0 (4) | 21.5 (3) | 21.9 (2) | |
| | Oct 20 | 5880 | | | | −170[d] |
| | Oct 21 | 7681 | 23.1 (4) | 27.4 (1) | 21.6 (4) | |
| 1989 | Feb 22 | 5616 | 21.5 (4) | 21.6 (2) | 20.4 (3) | |
| | | 5880 | | | | −174[d] |
| | Feb 23 | 7681 | 22.1 (4) | 20.2 (1) | 21.0 (4) | |

[a] The sharp (interstellar/circumstellar) absorption is at – 22 km s$^{-1}$.
[b] The number in parentheses is the number of lines contributing to the mean velocity. Estimated errors are less than ± 2 kms $^{-1}$.
[c] Sharp emission.
[d] Broad absorption.

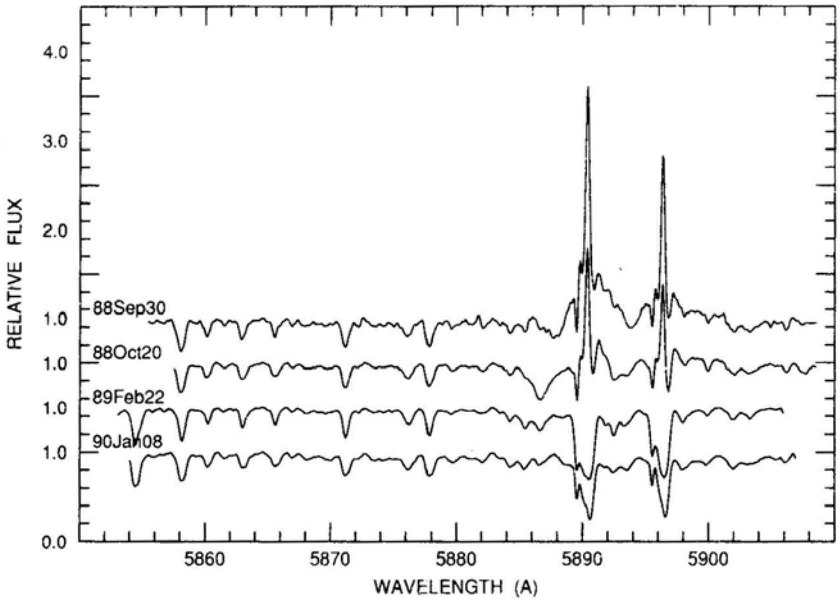


**Figure 1.** The spectrum of R CrB around the Na I D lines. Three spectra obtained during the 1988–1989 decline and a spectrum at maximum light are shown.

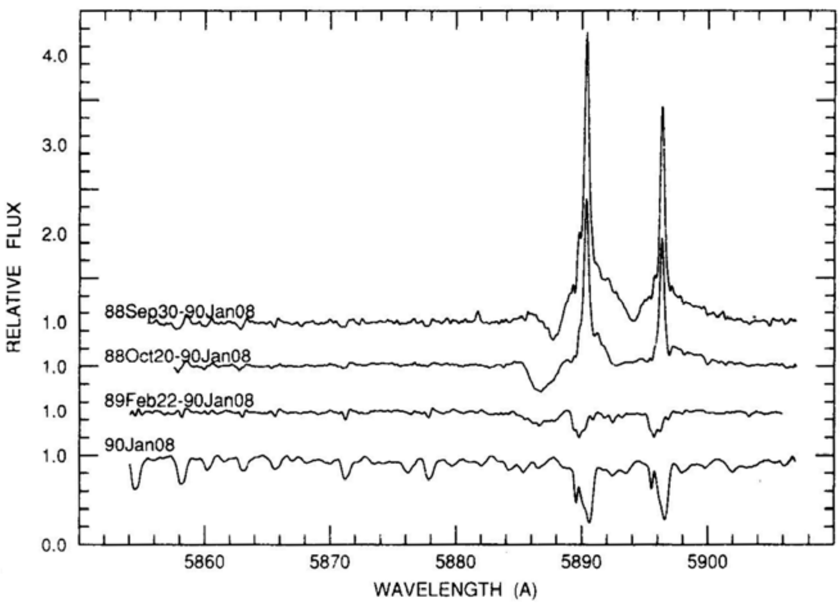


**Figure 2.** Three "differenced" spectra (see text) of R CrB derived from the spectra shown in Fig. 1. The spectrum at maximum light is also shown.

monitor the lines at maximum light. It should be noted that the photospheric absorption lines were used to set the individual spectra onto a common wavelength scale. Hence, velocity differences from exposure to exposure are ignored in the construction of the differenced spectra. Estimates of radial velocities were made using either the telluric $H_2O$ lines or hollow cathode (ThAr or FeNe) lines as a reference. These velocities are given in Table 1. Since the small variations are consistent with the known low amplitude velocity variations seen at maximum light (Raveendran, Ashoka & Rao 1986), we assumed that the absorption lines could be shifted into coincidence before the subtraction.

Our spectra show no evidence for broad emission in the He I 5876 Å feature. Such a component at Na I D is obvious in the original and the differenced spectra for 1988 September 30. If the broad 5876 Å profile is assumed to be similar, we may set an upper limit to its flux of about 5 per cent of the continuum flux. Unfortunately, we do not know whether the He I 3889 Å contributed a broad emission line at this minimum. Observations of previous minima would suggest that the latter line must have been present.

The Na I D lines at minimum show a complex profile superimposed on the photospheric spectrum: a sharp intense emission and a weaker broad emission line with a blue-shifted absorption component. Note that the weak, sharp emission component to the blue of the strongest component on 1988 September 30 is the terrestrial Na I D emission. On the assumption that the emitting layers are optically thin in the Na I D lines, the differenced spectra will correctly represent the emission profiles. The assumption is also valid for the case where the optically thick (or thin) emitting layer is not projected onto the photosphere. The blue-shifted (–22km $s^{-1}$) sharp absorption line seen in the spectrum at maximum light is contributed by circumstellar or interstellar gas. This gas must impose an absorption line on the emission profile that is not removed by the procedure of subtraction: a more refined procedure would allow this line to be removed.

The sharp Na I emission lines have relative fluxes in the ratio $D_1/D_2 \sim 0.6$(1988 September and October). Since these are slightly higher than the ratio (0.5) for an optically thin layer, the emitting layer is marginally optically thick. It is unlikely that this condition seriously compromises the use of the differenced spectra. The lines are blue-shifted with respect to the photospheric lines by about 2 km $s^{-1}$ when the mean photospheric velocity of + 23 ± 1 km $s^{-1}$ is adopted for high excitation C I lines. This small shift is in contrast to the shift of about 10 km $s^{-1}$ (CLB) determined from the sharp Ti II and Sc II lines about 50 days earlier (1988 August). CLB's measurements of the Na ID lines appear to confirm that the lines are less blue-shifted than the other lines. The line width (FWHM) of the stronger narrow emission component is about 20 km $s^{-1}$ which is the instrumental width provided by the emission lines of the hollow cathode lamp. The Na I emission lines are substantially narrower than the photospheric absorption lines (FWHM ~ 44 km $s^{-1}$ without correcting for the instrumental width).

The emission component of the broad P Cygni profile is more prominent on 1988 September 30 than on 1988 October 20, but the blue-shifted absorption component is much stronger on the latter date. The half width of the emission at its base is 250 ± 10 km $s^{-1}$ (1988 September 30) (as determined from the redwing of the $D_1$ line in the differenced spectrum). This value is typical of the broad emission lines seen in the earlier declines of R CrB (Rao 1981). The line is approximately centred on the photospheric velocity.

The differenced spectra show that the blue-shifted absorption component is most prominent on 1988 October 20. On 1988 September 30, the broad absorption was at a velocityof –140 km $s^{-1}$ relative to the photosphere. The absorption on1988 October

20 is centred at about –190 km s $^{-1}$ relative to the photosphere. This absorption component is much weaker on 1989 February 22, but at the velocity observed 4 months earlier. According to CLB high velocity emission was first seen on 1988 July 30 when $m_V$ = 7.9 and the decline was about 3 weeks old. CLB confirm that the absorption was present on 1989 February 2, 17 and 18, but was apparently absent on 1989 March 21. It must be noted, however, that CLB's comments and velocity estimates are based on the observed and not differenced spectra. Furthermore, their spectra are at a modest resolution and S/N. We suggest that examination of differenced spectra is needed to be certain of the first appearance of the high velocity absorption component.

High-resolution spectra of the Na ID lines at maximum light in 1990 May are shown in Fig. 3. These spectra show that the sharp absorption line at – 22 km s $^{-1}$ in the 1990 January 8 spectrum (Fig. 1) consists of two components or possibly a single absorption line with sharp emission superimposed. The sharp Na ID line at –22 km s $^{-1}$ was reported by Keenan & Greenstein (1963), but not resolved by them into two components. Our new spectra show structure in the deep core of the Na I D photospheric lines. Moreover, similar spectra obtained in the earlier months show that this structure is variable. We identify this structure as the blue-shifted chromospheric emission line.

*The K I 7664 Å Lines.* Examination of our three spectra shows that there are no large changes in the profiles of the K I resonance lines. An absence of strong chromospheric and circumstellar emission in the K I lines at minimum light is not unexpected. The doublet ratio shows that the Na ID lines are not very optically thick. Then, the Na and K emission lines will be roughly proprotional to the elemental abundances. Since the relative abundances of elements heavier than oxygen appear to be solar (Schönberner

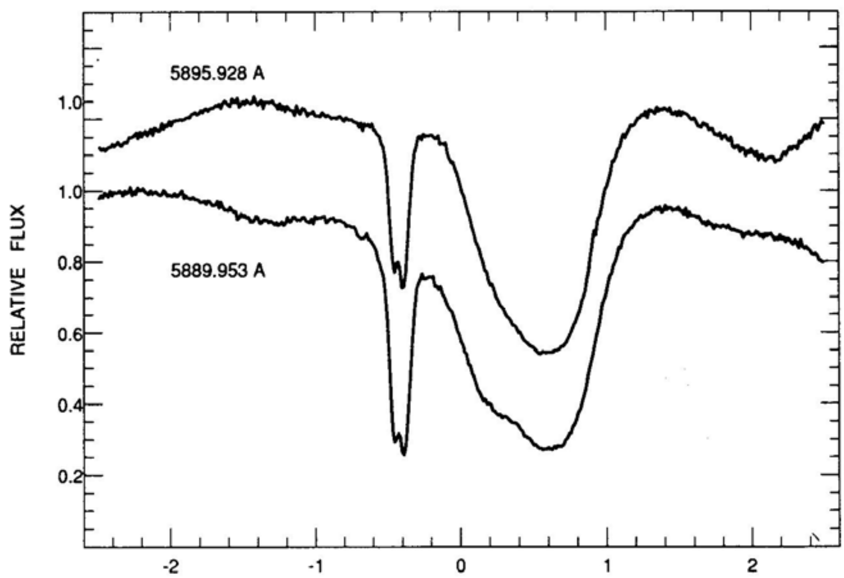


**Figure 3.** High-resolution spectra of the Na I D lines in the spectrum of R CrB near maximum light.

1975; Cottrell & Lambert 1982), the K I lines will be about a factor of 16 weaker than the Na I D lines. Our observations are consistent with this estimate. Similarly, the absence of high velocity absorption components in the K I lines is due to the low abundance of K.

*The $C_2$ Swan System 0–1 Band.* The two spectra of the 0–1 bandhead at 5634 Å are shown in Fig. 4. The $C_2$ bandhead is appreciably stronger at minimum light. $C_2$ lines shortward of the blue-degraded head are also strengthened. This is shown with remarkable clarity in the ratioed spectrum in Fig. 4. A ratio of the minimum and maximum spectra is more appropriate for separating the spectrum of the cooler layers giving the $C_2$ band. However, tests show very little difference between the 'differenced' and the 'ratioed' spectra. The ratioed spectrum is compared in Fig. 5 with a spectrum of the cool RCB WX CrA taken in 1989 July with the Cassegrain echelle spectrometer at the 4 m telescope of the Cerro Tololo Inter-American Observatory. The line for line correspondence between the two spectra is good evidence that the additional $C_2$ absorption in RCrB at minimum is provided by gas at about the photospheric temperature of WX CrA (~ 4000–5000 K) and not the low temperatures expected in the circumstellar shell. The gas is too cool to contribute absorption lines to the high excitation He I and C I lines and other lines seen in our spectra. The purity of the ratioed spectrum shows that the contributing $C_2$ molecules have the radial velocity of the photosphere. Such a conclusion was reached by Rao, Giridhar & Ashoka (1990) for the atoms contributing enhanced neutral metal lines in R CrB during the initial decline of an earlier minimum.

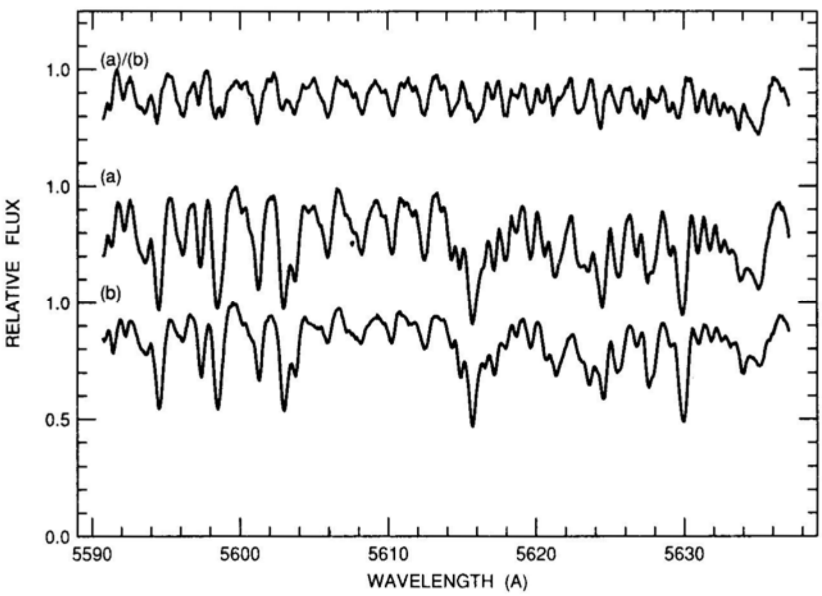


**Figure 4.** Spectra of R CrB around the $C_2$ Swan 0–1 bandhead at (a) minimum (1988 October) and (b) near-maximum (1989 February) light together with the "ratioed" spectrum (top spectrum).

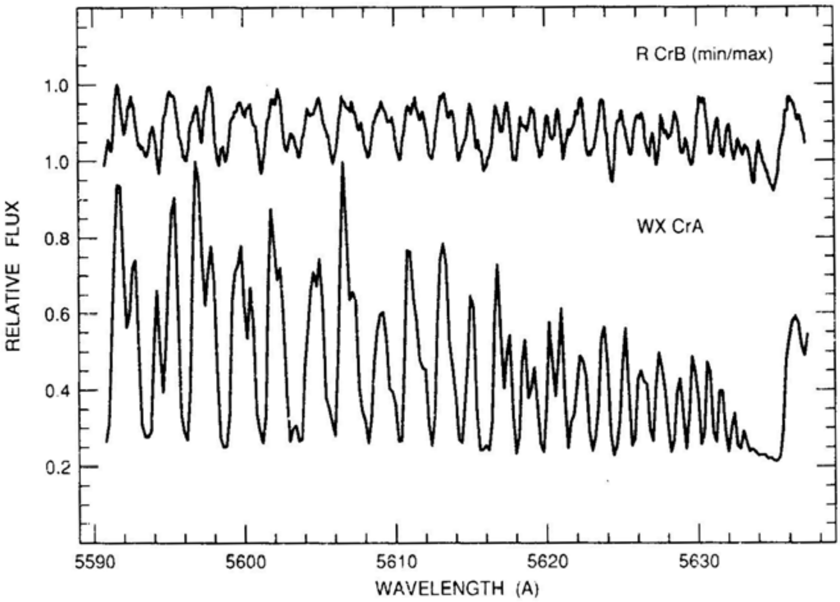


**Figure 5.** The $C_2$ 0–1 bandhead in the "ratioed" spectrum of R CrB and a spectrum of the cool RCB star WX CrA.

## 3. Comments on a model of RCB decline

### 3.1 *A Synopsis of the Model*

The suggestion that the decline of an RCB was due to clouds of carbon dust near the star was made more than 50 years ago (Loreta 1934; O'Keefe 1939). A variety of observations confirms this suggestion. Questions remain unanswered about the location of the dust, and in particular, about the trigger that leads to the production of the dust. In the following remarks, we discuss a popular empirical model that is reviewed by Feast (1986).

This model supposes that an RCB star ejects a puff or spray of dust. At a single ejection dust is ejected into a cone with a semi-angle of about 20°. One or two ejections occur in each pulsation cycle of the RCB. The ejection points are randomly distributed above the stellar surface. Deep minima are caused when an ejection point is on or near the line of sight. The circumstellar shell whose infrared radiation provides an RGB's infrared excess represents the debris of many ejections and emits, therefore, a relatively constant infrared flux. Dust in a fresh ejection and in the circumsteller shell is expelled from the star by radiation pressure. Gas is mixed with the dust and dragged outward at a velocity less than that of the dust. Fadeyev (1988) treated the problem of carbon dust condensation in RCB stars based on the empirical model stated above and could successfully model the light curves.

Can the empirical model account for the key spectroscopic signatures of a decline? Our discussion will be made with reference to Fig. 6. Dust assumed to form at a location P is driven radially outward by radiation pressure and dispersed laterally. In the figure we show the dust cloud as a thin shell. It is possible that dust formation

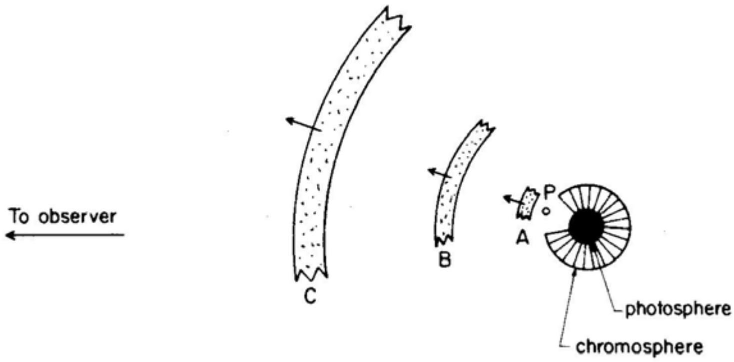


**Figure 6.** A model for shell formation and ejection around R CrB. Dust formation occurs near point P. Three snapshots are shown of a dust cloud moving away from the star and expanding laterally.

continues for an extended time so that the shell is thick. The location of P is quite uncertain. It is presumably at or above the distance (a few stellar radii) at which the equilibrium temperature of small grains is less than the sublimation temperature. In Fadeyev's model the dust condenses at ~20 $R_*$ from the ejected gas. In Fig. 6, we show the chromosphere to be quenched below P but this is not demanded by the observations. The trigger for dust formation may be related to turbulence or the pulsation of the photosphere. A density enhancement caused by pulsation may lead to dust condensation (Fadeyev 1988). Presence of turbulence is indicated by the large widths of the photospheric lines. Such turbulence may heat the chromosphere. Perhaps a few large (or small) turbulent elements provide the bulk of the heating. As their numbers vary stochastically it may be possible for the chromosphere to cool sufficiently to allow formation of dust. A somewhat similar explanation was proposed by Wdowiak (1975) for dust formation in a granular or supergranular network in R CrB. The carbon grains may initiate further cooling and additional grain formation.

In the early phases of the decline when the leading edge of the dust cloud is at point A (Fig. 6), the principal spectroscopic consequence is, as observed a dimmning of the photospheric spectrum. The photometric consequence of an optically thick cloud spreading across the visible hemisphere is readily shown to be a large dimming for a modest change of colour; *i.e.*, $R = \Delta V/\Delta(B–V)$ is large (Pugach 1984). The star will become bluer as the chromospheric emission lines provide the dominant contribution; CLB refer to this behaviour as a 'blue decline'. If the initially optically thin cloud quickly covers a large portion of the visible photosphere and becomes increasingly optically thick, the star will first become redder as it is dimmed; CLB refer to this as a 'red decline'. The 1988–1989 decline was a 'blue decline' (CLB).

When the dust cloud is at point B, the photosphere appears fully covered and the emission line spectrum from the unobscured portions of the chromosphere must dominate the observed spectrum. An earlier appearance of the emission lines will depend on their brightness relative to the photospheric continuum. CLB reported emission lines at $m_V = 7.4$ in the decline (*i.e.*, the photospheric flux was reduced by a factor of 4.4) and a filling in of the absorption lines was detected even earlier. In the 1949 decline, the sharp emission lines were seen at $m_V \sim 10$, but were not seen on earlier plates at $m_V \sim 8.5$when the photospheric flux was about 10 percent of its normal value.

Continued development of the cloud will lead to obscuration of the chromosphere and to a steady weakening of the chromospheric emission lines. Furthermore, one expects, as is observed (Payne-Gaposchkin 1963; CLB), the character of the emission line spectrum to change as the height above the photosphere of the unobserved area increases.

The slow recovery from the minimum occurs as the dust cloud expands and disperses. It is to be expected that, in the break-up of the cloud, the photosphere and chromosphere will brighten in unison. Therefore, the chromosphere's emission lines will be much less prominent in the recovery phase than in the decline to minimum when areas of the chromosphere are unobscured but the photosphere is obscured. This difference between the decline and the recovery phases is observed—see Rao, Vasundhara & Ashoka (1986), who observed the 1972 minimum of R CrB, and Alexander *et al.* (1972) for RY Sgr. Since the fading to and recovery from minimum light are controlled by different processes, it is not surprising that the timescales for the two phases are different.

### 3.2 *The Sharp Emission* (*Chromospheric?*) *Lines*

The observed blueshift (about $\leqslant 10$ km $s^{-1}$) of the sharp emission lines relative to the mean photospheric velocity suggests an expansion of the region that we term the chromosphere—see Section 3.4. Since such a shift is observed at each minimum, it must be a general property of the chromosphere during a decline. In order to obtain further information about the chromosphere, we searched at maximum light for chromospheric emission in the deep cores of photospheric lines. As noted earlier, the Na I D lines show highly asymmetric cores that we attribute to filling in by blue-shifted chromospheric emission. Confirmation of this identification is provided by observations of a line that is prominent in chromospheric spectra during the decline phase.

High-resolution spectra were obtained of the Sc II 4246.8 Å line. A comparison of the Sc II line in R CrB at maximum light and in the normal F supergiant $\delta$ CMa is offered in Fig. 7; $\delta$ CMa was shown by Cottrell & Lambert (1982) to be a fair match to R CrB. The core of the Sc II line in R CrB is not that expected of a strong photospheric line. Since the core of this line in $\delta$ CMa is smooth and symmetrical, the distorted core in R CrB is probably not due to a blend of photospheric lines. We attribute the distortion to the superposition of a chromospheric emission line on the deep core of the photospheric line with the former shifted relative to the latter by about – l0km $s^{-1}$. Moreover, as was found for the Na I D lines, the chromospheric contribution is variable. These high-resolution observations suggest that the blue-shifted chromospheric lines seen in a decline are present at maximum light and possibly a permanent feature of R CrB.

If the fluxes of the chromospheric components to the Na I D and Sc II lines are unchanged in a decline, they will equal the photosphere's continuum flux when the photosphere has declined in brightness by a factor of about 10. CLB first recorded "Sc II, Ti II, and Fe II emission" at $m_v \leqslant 7.4$ or 1.6 magnitude below maximum light and on earlier spectra at $m_v$ = 6.8 and 7.3, the photospheric lines were filled in to a noticeable extent. CLB observed first appearance of chromospheric emission lines is roughly consistent with our estimate based on the emission components identified at maximum light.

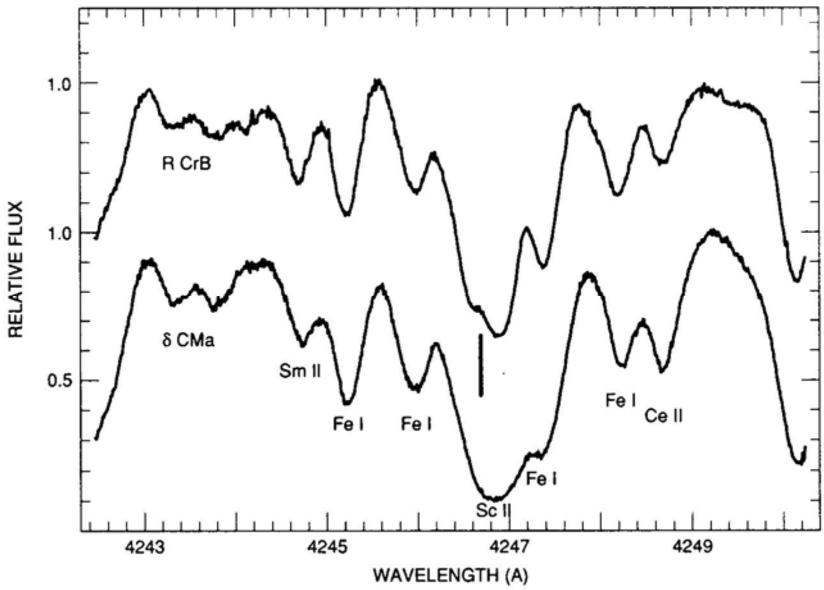


**Figure 7.** High-resolution spectra near 4247 Å of R CrB near maximum light and the F supergiant $\delta$ CMa. The blue-shifted chromospheric emission in the core of R CrB's Sc II 4246.8 Å line is marked by the short vertical line.

One supposes that the blueshift arises from an expansion of the chromosphere. If the chromosphere is approximately spherically symmetric, an optically thin emission line seen from areas unobscured by a cloud at point B or at later times should be unshifted with respect to the photosphere, but broadened by an amount of the order of the expansion velocity. For large optical depths, emission might be expected to come predominantly from the blueshifted gas nearer the observer, but thanks to the velocity gradient along the line of sight, large optical depths in the lines will be difficult to maintain. Accurate line profiles determined from differenced spectra such as those in Fig. 2 would be of real interest. The sharp Na I D lines at the time of our observations show only a very small blueshift and the line profiles are qualitatively consistent with formation in an almost stationary chromosphere.

The onset of dust formation may lead to local changes in the chromospheric structure. If, for example, the chromosphere is quenched below the site of dust formation (point P, Fig. 6), the reduced gas pressure may cause the bordering chromospheric regions to flow into the quenched regions. This flow would lead to a blueshift of the chromospheric lines with a maximum value approximately equal to the sound speed (*i.e.*, about l0 km $s^{-1}$) . The regions of the quenched chromosphere are presumably the site for the $C_2$ molecules contributing the enhanced molecular lines. If the chromosphere could be observed at a time when dust was forming at a point on or near the far side of the star, the chromospheric lines may show a redshift This test should be possible, in principle, using the ultraviolet emission lines.

If the site of dust formation is placed in or below the expanding chromosphere, the contrast of the chromospheric line relative to the photospheric continuum will increase as dust obscures the photosphere. Then, the chromospheric layers projected onto the photosphere will give the dominant contribution to the emission line spectrum and net blueshift will be recorded as long as the chromosphere is expanding. However, this model raises difficult questions: can a chromosphere of high density (Payne-Gaposchkin 1963) be maintained with a substantial content of dust in or above it? Fadeyev (1983) proposed that the sharp emission lines come from a shock front and not a semi-permanent chromosphere.

An enhancement of the photospheric $C_2$ lines is, in principle, achieveable by an obscuration that is most severe towards the centre of the disc. Under such special circumstances, the photospheric spectrum is primarily that of the limb in which lines of $C_2$ and other low excitation lines are expected to be enhanced and high excitation lines are weakened. We reject this idea that the enhancement of the $C_2$ is simply a centre-limb effect because it demands a special geometry with respect to the observer for what appears to be a common property of R CrB declines and because we do not see the predicted weakening of the high excitation lines.

### 3.3 *The High Velocity Cloud*

The high velocity absorption components seen in the Ca II H and K and Na I D lines are attributed to gas ejected with the dust cloud. If this gas were unrelated to the cloud, the high velocity components should be seen on occasions at maximum light. Such components have never been reported, although an intensive search is yet to be made. It is supposed that the gas is accelerated to speeds of 100 to 200 km $s^{-1}$ by the dust that is driven out by radiation pressure. Detailed observational studies, as yet unavailable, of the development of high velocity components could reveal much about the growth of the dust cloud and particularly because the absorptions can be detected against the bright photospheric continuum that drowns the faint chromospheric emission lines. In the 1988-1989 minimum of R CrB the components in the Na I D lines may have been detected as early as 3 weeks into the decline (CLB). Accurately differenced spectra of the Na I D lines will be needed to detect the onset of weak components that may appear first at low velocity as a deepening and broadening of the photospheric lines. The cloud is probably more easily detected in the Na I D than the Ca II H and K lines because the latter's photospheric lines are broader and deeper and the stellar flux is higher at 5890 Å than at 3930 Å. Early in the decline, the equivalent width of the components will depend on a cloud's projected area. Careful searches for these components in low excitation lines would be valuable in setting limits on the physical conditions in the clouds.

The high velocity absorption components which persist through to the advanced phases of the recovery from minimum are presumed to vanish as the cloud of dust and gas expands so that the column density along the line of sight to the star decreases. This presumption is consistent with the Na I D profiles of 1988 October and 1989 February. The total distance traversed by the cloud in the time that it gives a detectable high velocity component is a small fraction of the radius of the circumstellar shell responsible for the infrared excess. The 1988–1989 cloud moved at about 150 km $s^{-1}$ (relative to the star) for about 200 days if we accept CLB's early detection of the Na I D components; *i.e.*, the distance travelled is about 40 $R_*$ $\simeq$ 4000 $R_\odot$. The grains contributing the infrared excess must be at about 200 $R_*$ (Hartmann & Apruzese

1976). The radiation emitted by the hot grains in the freshly ejected clouds is at shorter wavelengths and may be detectable on occasions above the photospheric radiation from the obscured star (Shenavrin *et al.* 1979).

Radiation pressure on the grains is considered to drive the mass loss following dust formation. Around cool oxygen-rich luminous supergiants (*e.g.*, Betelgeuse) and asymptotic giant branch stars (*e.g.*, the Mira variables), the stellar wind has an observed expansion velocity of 10 to 20 km s $^{-1}$ These winds have been modelled successfully (Tielens 1983) with radiation pressure on silicate grains as the driving force. It is reasonable to ask why the gas in the temporary wind of a RCB has the much higher expansion velocity of 100 to 200 km s $^{-1}$. (These observed velocities refer to the gas ($V_g$). The dust grains are driven out at a higher velocity ($V_d$)). We may note several reasons why higher wind speeds are likely. First, graphite grains present a larger cross-section to photons than silicate grains; Wickramasinghe (1972) estimates the ratio of the radiation to gravitational forces to be approximately 100 times higher for graphite grains. Second, the condensable mass fraction of material (grains) in an RCB atmosphere is higher by a factor of 2 to 4 than that of silicate material in an oxygen-rich giant's atmosphere; this fraction is set by the appropriate elemental abundances, but the actual mass fractions depend on the efficiency of grain formation. Third, the photon supply given approximately by $R_*^2 \quad T_{eff}^4$ is higher for RCB stars. Hartmann & Apruzese (1976) calculate that; in the absence of gas, the graphite grains around R CrB achieve aterminalvelocity of 600 km s $^{-1}$ if formed at $R$ ~ 300R*; this velocity scales as $R^{-1/2}$. The carbon condensation model proposed by Fadeyev (1988) (where the dust condenses from ejected gas at ~20 R*) shows that the gas is accelerated to velocities ~100 km s $^{-1}$,but the drift velocity between gas and dust never exceeds ~20 km s $^{-1}$ and, hence, grains are most probably not destroyed by sputtering through gas-grain collisions.

A high velocity component to the He I 10830 Å line was seen by Querci & Querci (1978) when the star was rising to maximum following a minimum about 6 months earlier in mid-1977. This absorption component at about – 230 km s $^{-1}$ was seen by Zirin (1982) on a spectrum taken in 1978 July when the star had returned to maximum light. Clearly, the high velocity gas must be hot and dense in order to provide a strong absorption feature at 10830 Å. Zirin's observation suggests that the high velocity feature may be a characteristic of the spectrum near maximum light. Querci & Querci (1978) reported the absorption component to be part of a P Cygni line. Unfortunately, it is unclear from the description of their low resolution spectrum whether the emission component of the P Cygni line is a narrow chromospheric line or a manifestation of the broad emission line seen at He I 3889 Å. We suppose that the latter interpretation is the more likely. Emission was not detected by Zirin.

### 3.4 *The Broad Emission Lines*

The broad emission lines are undisplaced relative to the photospheric velocity and, hence, the emitting volume is considered to be roughly spherically symmetric about the star. The high velocity absorption components of the same lines are attributed to gas in the new clouds. Later,these clouds will form part of the circumstellar shell giving the infrared excess. Since similar expansion velocities are derived from the velocity of the absorbing clouds near minimum light and the width of the broad emission lines, the former appears to be a terminal velocity. This velocity is greater than the escape velocity.

The expanding dust shell may also account for the veiling of the photospheric absorption lines seen at the deepest minima of R CrB. At these minima, the absorption spectrum may consist of two components: (1) faint photospheric light transmitted by the new and other clouds along the line of sight, and (2) photospheric light from the entire stellar surface scattered into the line of sight off grains in the circumstellar shell. If the second contribution exceeds the first, the absorption line spectrum will appear washed out; *i.e.*, veiled because the shell's expansion velocity is several times the intrinsic width of the photospheric lines, and hence, the lines in the spectrum of this scattered and Doppler-shifted light will be greatly broadened. Scattering not only broadens the absorption lines, but also introduces a redshift as pointed out by Rao (1974, 1975) and Forrest (1974). The redshift of absorption lines that never go into emission (C I lines) was ~ 5–19 km s $^{-1}$ at the 1960 minimum. Observations at the 1962 minimum were interpreted by Rao (1974,1975) using a Mie scattering model for a cloud of graphite grains and indicate expansion velocities of 40–80 km s $^{-1}$ for the dust.

A key question is whether the broad emission lines are permanent features of the star or appear only at a minimum. The sharp emission spectrum is dominated by low excitation lines of singly ionized metals characterised by $T_e$ ~ 5000 ± 500 K, $N_e$ ~ $10^{11}$ cm $^{-3}$ (Payne-Gaposchkin 1963; Rao 1974),but no He I sharp emission lines are present even though He I is one of the dominant species showing broad emission lines. IUE low resolution spectra of R CrB show C II] 1335 Å emission at a roughly constant flux during light maximum as well as during minimum (Holm & Wu 1982), Unfortunately, the quality of the available IUE spectra does not permit the sharp and broad components of the C II line to be distinguished. The He I 3889 Å, Ca II H and K broad lines showed asimilar behaviour in the early 1962 light minimumof R CrB: the line flux remained fairly constant even though the equivalent widths varied from 3 to 14 Å (Rao, unpublished observations). This behaviour suggests that the broad emission lines may be permanent features. Even the C III] 1909 Å line seen during the 1983 minimum may belong to the broad emission region. The presence of C III] 1909 Å and the upper limit ( 1) to the flux ratio of C II] 2325 Å / C II] 1335 Å estimated from the high resolution IUE spectrum obtained by one of us (NKR) at maximum light leads to a $T_e \sim 2 \times 10^4$ K and $N_e \sim 10^{9-10}$ cm $^{-3}$ according to recipes given by Brown & Carpenter (1984).

A question regarding the broad emissions is the excitation mechanism. The fact that even a cool RCB star like U Aqr ($T_{\rm eff} \lesssim$ 5000 K) shows He I 3889 Å strongly in emission during the light minimum (even stronger than Ca II H and K lines—Bond, Luck & Newman 1979) indicates radiative excitation is unlikely. Moreover, there is no obvious source of radiation unless the presence of an unseen hot binary component is invoked. Another puzzle about the broad emission line region is the anomaly regarding the He I lines, namely 5876 Å is weaker (in fact, undetected) than 3889 Å and even weaker than 7065 Å (Rao 1981). Such anomalies seem to require the gas to be at $N_e \sim 10^{10}$ cm $^{-3}$ and $T_e \sim 2 \times 10^4$ K and to have high optical depth in the 3889 Å line (Almog & Netzer 1989; Surendiranath, Rangarajan & Rao 1986). A full description of the broad line spectrum from the ultraviolet to the near infrared should be a major goal of observations in a future decline.

The high electron density indicated by the He I lines and by the C II lines (if they belong to the broad line region) suggests that the broad lines may be formed in the upper layers of an extended expanding chromosphere reminiscent of the models developed for T Tauri stars (Hartmann, Edwards & Avrett 1982) and hybrid supergiants (Hartmann, Dupree & Raymond 1981) where the chromosphere is supported by Alfvén waves. The models have a lower chromosphere that is cool ($T_e \sim 5000$ K), expanding slowly and mildly turbulent and, hence, a plausible site for the sharp emission lines. For a mass loss rate of $2 \times 10^{-8}$ $M_\odot$ yr$^{-1}$ (*e.g.*, model 1 of Hartmann *et al.* 1982), the temperature increases to about 30,000 K and the wind attains its terminal velocity of about 200 km s$^{-1}$ at a height of 2 to 3 $R_*$. The He I lines are formed in the hottest layers of the wind. The Na I D lines are formed in the cooler outer reaches of the wind. In these models, the higher the mass loss rate the cooler is the wind temperature.Heating is by the dissipation of Alfvén waves with magneticfields of 300–500 G in high gravity stars (T Tauri stars) and 1–10 G in case of supergiants for mass loss rates of ~ $10^{-8}$ $M_\odot$ yr$^{-1}$. The scaling laws suggest that the mass loss rate of R CrB requires a field strength of about 40 G for the wave flux of about $10^5$ erg cm$^{-2}$ s$^{-1}$ ($M \sim 1\ M_\odot$ and $R_* \sim 100\ R_\odot$ is assumed). This flux is roughly equal to the emitted flux in R CrB's broad emission lines (~$5 \times 10^4$ erg cm$^{-2}$ s$^{-1}$ if $R_*$ = 100 $R_\odot$, $d$ = 1.3 kpc). The photospheric lines of R CrB are broad and the inferred turbulence of about 20 km s$^{-1}$ may suffice for generations of the waves. In this model the dust may form in the cool outer reaches of the wind where the wind velocity is at its terminal value. It is possible that the primary site for dust formation is, as indicated earlier, above a region where the chromosphere has been temporarily quenched. The trigger for dust formation remains unknown. The [O II] 3727 Å emission discovered by Herbig (1949) may come from the outer reaches of the circumstellar shell or a fossil H II region (Rao & Nandy 1986).

## 4. Concluding remarks

Our high-resolution spectra taken at minimum light show that the $C_2$ Swan absorption bands are stronger than at maximum light, The cool gas responsible for the enhancement of the $C_2$ bands and of low excitation metal lines is stationary with respect to the photosphere. Our spectra extend the earlier finding (Rao, Giridhar & Ashoka 1990) about the line enhancements at minimum light. The Na I D lines at minimum light are strongly in emission with a dominant sharp component and a much broader component. These components and an associated blueshifted absorption component are common features of R CrB in decline. Photospheric lines in the several spectral regions observed at minimum light have profiles that are similar to those observed at maximum light; *i.e*., the photospheric spectrum was not "veiled".

Further progress in understanding the atmospheric changes occurring during a decline of R CrB requires intensive spectral and temporal coverage. This requirement may be satisfied only through international collaboration. Although the declines deserve especial consideration by observers, our observations of selected lines show that much can still be learned from high resolution spectra taken at maximum light.

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