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Spectroscopic studies of R CrB during light minima: absorption spectrum

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SUMMARY

R CrB was observed during the 1986 shallow minimum to study the spectral changes taking place during light minimum as compared with the spectrum at maximum light. The absorption spectrum at this minimum is very similar to the spectrum seen during the early decline of the 1963 light minimum. We find an enhancement of molecular bands of C_2, CN and low excitation atomic lines during these phases. We also note an absorption feature at λ4050.5 – probably due to C_3 in the early decline of the 1963 and 1986 minima.

We have estimated the atmospheric parameters for R CrB during light maximum and minimum by measuring equivalent widths for a sample of 63 lines on these spectra and comparing them with theoretically computed line strengths using the model atmospheres of Schönberner with various temperatures and microturbulent velocities. Our calculations do not indicate any drastic change in effective temperature and microturbulence between light maximum and minimum. It appears that regions with enhanced molecular absorptions are required to explain the absorption spectrum during light minimum.

1 INTRODUCTION

R CrB is a prototype of a group of carbon-rich, hydrogen-deficient stars that undergoes a sudden drop in its brightness, ranging from small dips of ~0.5 to 8 mag or more at irregular intervals. The occurrence of these irregular light minima is attributed to the formation of carbon dust around the star (Loreta 1934; O'Keefe 1939). From the presence of observed infrared excesses (Forrest, Gillet & Stein 1972; Glass 1978), visual extinction and reddening during the light minimum (Rao, Vasundhara & Ashoka 1986) and the presence of a broad absorption feature at $\lambda\lambda$2400–2500 in the ultraviolet extinction curve (thought to be caused by amorphous or glassy carbon grains by Hecht *et al.* 1984), it is believed that dust condenses in the circumstellar environment. However, the observational evidence relating to the processes of grain condensation during a light minimum is lacking (see Feast 1986 for a review), i.e. there are no observational indications that the atomic gas gets converted into polyatomic molecules and further to dust grains. Also, there is no observational evidence for the presence of intermediate stages in the grain condensation and hence for dust formation.

It is thought that in a normal deep minimum, the process of grain condensation is so fast that the circumstellar material becomes optically thick very rapidly – and hence we cannot study these intermediate stages. It is hoped that spectroscopic observations of shallow prolonged minima could give important clues towards the formation of dust grains. With this view we made spectroscopic observations of R Cr B during 1986 when it went through a shallow minimum.

2 OBSERVATIONS

Spectroscopic observations were obtained with the 1-m reflector of Vainu Bappu Observatory at Kavalur. Our spectra had a linear dispersion of 86 A mm^{-1} and were recorded on II aO plates. The spectra were obtained at two epochs, the first in the middle of the light minimum when the visual magnitude, V, was 7.2 (i.e. 1.4 mag fainter than at maximum) and the second at the end of the light minimum when the visual magnitude, V, was 6.2 (Fig. 1; Ashoka & Pukalenthi 1986).

These spectroscopic observations were compared with the spectroscopic observations made at light maximum

(V=5.8) at the same dispersion. Fig. 2 illustrates the spectrum in the region of the C_2 (1–0) Swan system obtained at two epochs $V\sim6.2$ (top spectrum) and $V\sim7.2$ (bottom spectrum). The dashed line superposed on both spectra is the spectrum at light maximum. Generally these spectra are dominated by absorption lines and are similar to those of F8 Ib supergiants (e.g. γ Cyg) with obvious peculiarities such as strong carbon lines and weak H I lines. The spectra of R CrB obtained at both epochs (i.e. when the star had recovered from the light minimum as well as being 0.4 mag fainter than the maxima, at the end of recovery) also resemble the spectrum at light maximum. However, the spectrum obtained at light minimum ($V\sim7.2$) shows the following changes with respect to the maximum light spectrum.

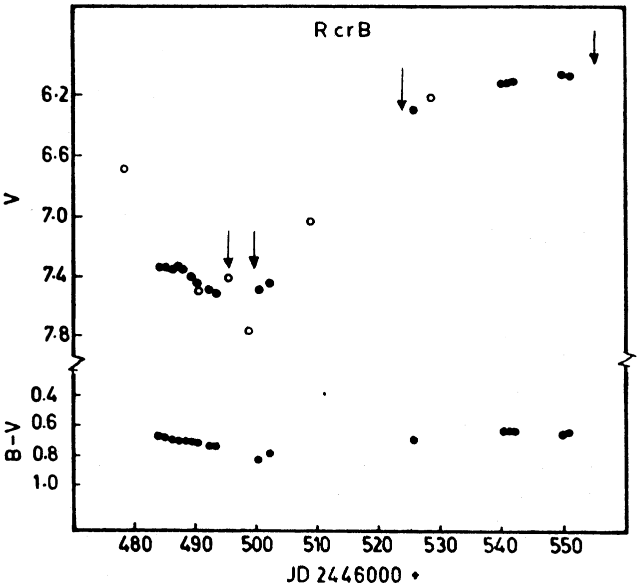

Figure 1. The light curve of 1986 minimum of R Cr B (Ashoka & Pukalenthi 1986), where the arrows indicate the epochs of spectroscopic observations.

(i) The C_2 Swan bands of the 1–0 sequence (Fig. 2) and the CN bands at λ4215 Å are much stronger. Also, the low-excitation atomic lines, particularly those of Fe I, Mn I etc., are strengthened.

(ii) Strong lines of singly ionized metals like Ti II, Sc II have become weaker.

(iii) The absorption lines of C I which have high-excitation potential ($\sim$7 eV) appear to be slightly weaker.

(iv) An absorption feature at λ4050.5 Å has become much stronger.

The above-mentioned observations were (further) supplemented by high-dispersion (16 A mm^{-1}) coudé spectra obtained by Dr G. H. Herbig during 1962 and 1963 deep light minima using the 3-m telescope of Lick Observatory. These spectra are denoted EC in Table 1 which contains the journal of observations. Both these minima are deep ($V\sim13$ and $V\sim13.5$) and the light curves are shown in AAVSO report 29. These coudé spectra were compared with the light maximum spectrum (EP1771) obtained during 1973 July with the coudé auxiliary telescope using the same spectro-

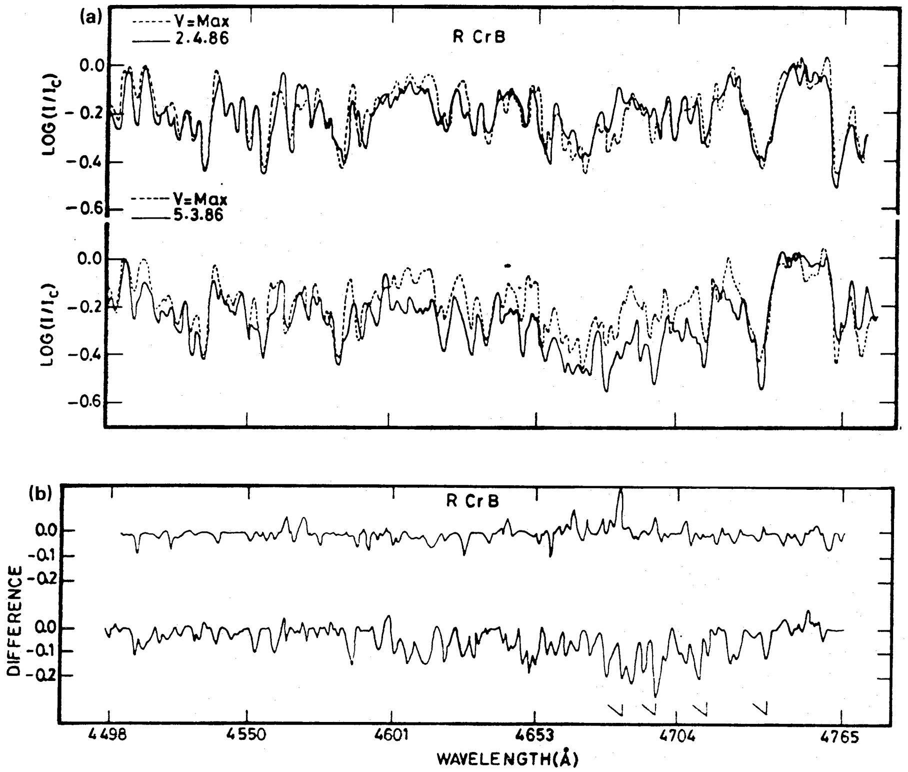

Figure 2. (a) The spectrum in the region of the C_2 (1–0) Swan system at the two epochs $V\sim6.2$ (top) and $V\sim7.5$ (bottom) the 1986 minimum. The dashed line is the spectrum at light maximum. (b) The differenced [log I/I_c max − log I/I_c min] spectrum with respect to maximum light for the two epochs. The enhanced C_2 bands (during the minimum) are marked.

graph and dispersion. The spectrogram obtained when the star was 2.7 mag fainter during the initial lightdrop in 1963 (EC2056) shows many characteristics similar to the light minimum spectrum obtained in 1986 and discussed earlier. The equivalent widths of molecular bands of CN and the C_2 Swan System are enhanced by a factor of 2 (Table 2). In addition to the molecular band strengthening, the low-excitation lines, particularly zero volt lines, of metals like Fe I, Cr I, Mn I etc. are significantly enhanced. However, the equivalent widths of C I lines are nearly constant. Fig. 3 shows the difference in line equivalent widths between the plates EC2056 (light minimum) and EP1771 (light maximum) as a function of excitation potential. Fig. 3 clearly indicates that the low-excitation lines are enhanced in strength during the early decline in light minima.

Table 1. Journal of observations.

Plate No.	Date of observation	*V*	Dispersion	Emulsion
EP1771	11-4-1973	5.8	16 Å mm^{-1}	II aO baked
EC2056	10-7-1963	8.5 d	16 Å mm^{-1}	103 aO
EC1676	11-12-1962	8.65 r	16 Å mm^{-1}	103 aO
EC1735	13-2-1963	7.2 r	16 Å mm^{-1}	II aO baked
Z48	2-4-1986	6.2 r	86 Å mm^{-1}	II aO
Z14	5-3-1986	7.5	86 Å mm^{-1}	II aO
Z286	12-9-1986	5.8	86 Å mm^{-1}	II aO baked

*d and r refer to the decline and recovery phase of the light curve.

In addition, similar to the 1986 minimum spectrum, an enhanced absorption feature occurs at λ4050.5 on this spectrogram (EC2056). This feature is weak or absent on the spectrograms obtained at the end of the 1962 minimum during the recovery phase (EC1676 and EC1735) at roughly the same magnitude ($V \sim 8.6$ and 7.2, respectively).

3 ANALYSIS

The absorption spectrum during the light minimum of 1960 was studied by Gaposchkin (1963) who noticed the strengthening of molecular bands. She interpreted the changes in the absorption spectrum as being due to increased microturbulence during light minimum with photospheric temperatures being almost unchanged.

To understand the effect of changing the physical parameters $T_{\rm eff}$ and $V_{\rm t}$ (microturbulence) on the maximum spectrum, and to explore the possibility of producing the minimum spectrum only by varying these parameters, we measured equivalent widths for a sample of 63 atomic lines in the spectrum EC 2056 at light minimum and also in EP 1771 at light maximum. We used model atmospheres for hydrogen-deficient stars computed by Schönberner (1975 – detailed models were kindly supplied by Dr Schönberner) and theoretically calculated the line strengths for these 63 lines for the atmospheric model with $T_{\rm eff} = 7000$ K, $\log g = 0.5$ and helium content He = 99 per cent (by numbers). The line equivalent width calculation was done using the single line version of a LTE spectrum synthesis code originally written by Sneden (1974) and modified by one of us (SG) to include the C I, C^-, He^- opacities appropriate to R Cr B atmospheres. The calculation of additional opacities is described by Giridhar & Rao (1986). These computed line strengths match fairly well with the observed equivalent widths for spectrum EP1771 taken at light maximum (over a wavelength range of λλ4000–4780) with a microturbulent velocity 8.0 km s^{-1}, although a slightly higher microturbulent velocity gives a better fit for strong lines of singly ionized metals, e.g. Fe II. The abundances given by Cottrell & Lambert (1982) represent the line strengths at light maximum fairly well. We calculated equivalent widths for these 63 lines again with different values of $T_{\rm eff}$, $\log g$ and $V_{\rm t}$ (microturbulent velocity) to be able to get a good match with observed equivalent widths measured at light minimum (EC2056). Because the high-excitation lines, e.g. C I and Fe II, are fairly sensitive to these parameters, any significant change in $T_{\rm eff}$, $\log g$ and $V_{\rm t}$ would manifest itself through substantial line strength variation of high-excitation lines. A change of 1 km s^{-1} in $V_{\rm t}$ results in a 10 per cent change in the computed equivalent widths and a change of $T_{\rm eff}$ by 200 K results in 11 per cent change in the equivalent width computed. Similarly, a change of 0.25 in the value of $\log g$ results in 8 per cent variation in the equivalent width computed. Since the accuracy in the observed equivalent widths is 5–10 per cent, the uncertainties in the derived atmospheric parameters are expected to be ±150 K in $T_{\rm eff}$, ±0.25 in $\log g$ and ±1 km s^{-1} in $V_{\rm t}$.

Table 2. Equivalent widths of molecular bands.

	λ	EP1771 *W* (m Å)	EC2056 *W* (m Å)
C_2*			
	4737	800 ± 100	1480 ± 100
	4715	760	1427
	4697	700	1400
CN*			
	4215	305 ±	800 ± 120
	4195	—	150 ± 80
C_3(?)			
	4050.5	—	124 ± 30
	3991.7	—	47 ± 20

*The equivalent widths of the bands at maximum are measured as excess absorption in R CrB over αPer in the wavelength region of the band (~7 Å) – Searle 1961. The equivalent widths at minimum are estimated from the excess absorption in EC 2056 over EP 1771.

Since the observed equivalent widths of the high-excitation lines do not show large variation between light maximum and minimum it is unlikely that the changes needed in $T_{\rm eff}$ and $V_{\rm t}$ to match the minimum spectrum are very large. It appears that $T_{\rm eff}$ and $V_{\rm t}$ vary between light maximum and minimum from 7000 to 6800 K and from 8 to 10 km s^{-1}, respectively. A trial calculation with $T_{\rm eff} = 6500$ K results in much reduced equivalent widths for high-excitation lines (e.g. C I) that are inconsistent with the observations. However, some of the zero volt lines and low-excitation lines (e.g. Mn I, Cr I) are much too strong in the observed spectrum with respect to the theoretical one. In brief, the minimum spectrum can be described as being similar to that of maximum except for the enhanced absorption due to low-excitation atomic lines and molecular bands of CN and C_2. These changes cannot be explained as an overall change in either $T_{\rm eff}$ or microturbulence. Note that the absorption due to molecular bands of CN and C_2 increases roughly by a factor of two.

We synthesized the spectral region between 4045 and 4060 Å using all the atomic lines falling in this wavelength range to identify the feature at λ4050.5 Å. We could match the spectrum at maximum light (EP1771) using Schönberner's model with $T_{\rm eff} = 7000$ K, log $g = 0.5$ (see Fig. 4). By further changing the temperature and microturbulence for the models we tried matching the observed spectrum at light (EC 2056) minimum. It appears that the spectrum at light minimum can be matched fairly well with models in the $T_{\rm eff}$ range 7000–6800 K and V_t 8–10 km s^{-1} (Fig. 5). The equivalent width data had also led to the same values. But the feature near 4050.5 Å cannot be matched at all. No reasonable identification with atomic lines could be found. The λ4050.5 feature is close to the strong band of the C_3 λ4050 group present in absorption in carbon stars (Swings, McKellar & Rao 1953), in the peculiar F supergiant CRL 2688 (Crampton, Cowley & Humphrey 1975) and in the emission spectra of comets. The laboratory wavelength of the band head is 4049.8 Å (Gausset *et al.* 1965) but the wavelength in CRL 2688 (Crampton *et al.* 1975) is 4050.6 Å similar to that in R CrB. The next strong feature of C_3 expected to be observed is at 3990.8 Å (lab) and was seen at 3991.5 in CRL 2688. There is an enhanced absorption feature in R CrB at 3991.7 Å. It is tempting to ascribe these features at 4050.5 and 3991.7 Å in R CrB to C_3 as they occur when C_2 and CN are strong. However, further confirmation is required.

In the above analysis the changes due to pulsation have not been considered because the amplitude of these pulsations seems to be small and the range in radial velocity is less than 8 km s^{-1} (Raveendran, Ashoka & Rao 1986). Also, the spectrum at maximum light does not appear to change much (Cottrell & Lambert 1982). (The change in $T_{\rm eff} \leqslant 200$ K.)

4 DISCUSSION

The absorption spectrum during the shallow minimum and in the early decline shows that, in addition to the normal maximum spectrum, additional absorption due to molecular bands and low-excitation lines occurs. The above analysis also shows that no drastic change in the atmospheric structure occurs (i.e. in $T_{\rm eff}$ or V_t). Recently, Holm & Doherty (1988) tried to explain the *IUE* spectrum of R CrB obtained during a small light minimum (of 0.5 mag depth) in 1982 as a combination of change in the photospheric temperature due to pulsation and some circumstellar dust obscuration. They find that, if the amount of obscuring dust varies not only with the drop in temperature but with a lag in time, their model gives the observed wavelength-dependence of the amplitude and phase shift of the light curves. They also state that the observed radial velocities seem to be consistent with the pulsation being the cause of temperature variations. The range in temperature required by them is ~1000 K during the light drop and the temperature minimum occurs about 12 d earlier than the visual light minimum. Our analysis of the absorption spectrum during the early decline obtained 20 d before it reached the minimum magnitude ($V \sim 12$) does not indicate such a large temperature change. Even the spectrogram obtained at the 1962 minimum at $V \sim 9.5$ about

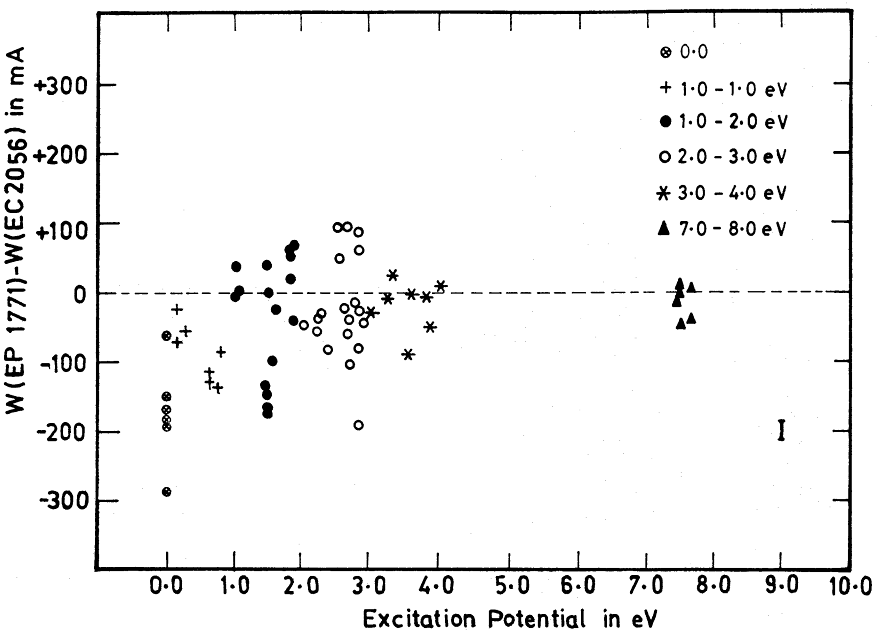

Figure 3. The differences in equivalent widths of absorption lines from the spectrogram obtained at the light maximum (EP1771) and the early decline phase of the 1963 minimum (EC2056) plotted with respect to the excitation potential. Note the enhancement of the low-excitation lines in the minimum spectrum.

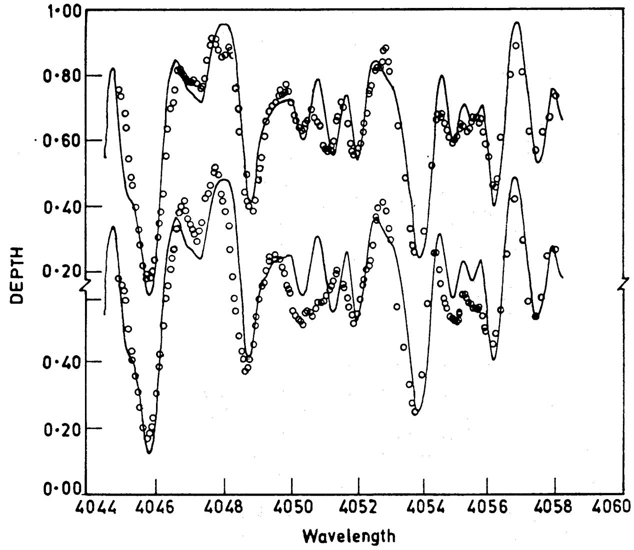

Figure 4. Computed spectrum (line) for $\lambda\lambda$4045 to 4058 Å with atmospheric model $T_{\mathrm{eff}}=7000$, $\log g=0.5$, $V_t=8.0$ km s^{-1} superposed on the (top) observed spectrum at maximum light (EP1771) and also on the observed spectrum at early decline EC2056 (lower).

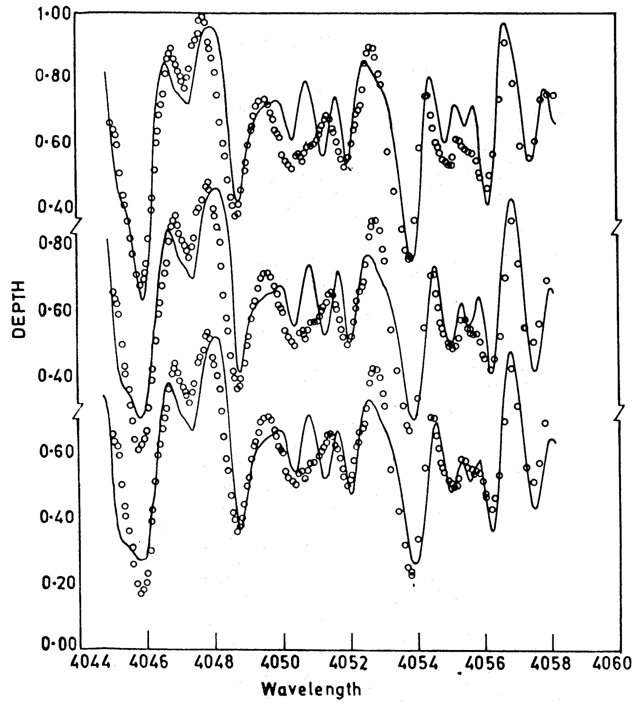

Figure 5. Computed spectrum with atmospheric model: $T_{\mathrm{eff}}=7000$ $\log g=0.5$, $V_t=8.0$ km s^{-1} (top); $T_{\mathrm{eff}}=6800$ $\log g=0.5$, $V_t=8.0$ km s^{-1} (middle); $T_{\mathrm{eff}}=6800$ $\log g=0.5$, $V_t=10.0$ km s^{-1} (bottom), superposed on the observed spectrum at early decline phase EC2056 (circles).

15 d after the start of the minimum and 17 d before it reached the beginning of the deep minimum ($V \sim 12$) does not show changes in the equivalent width of high-excitation C I lines; this is indicative of no major temperature change.

It is likely that regions with enhanced molecular absorption seem to be required in addition to the normal absorption spectrum. The radial velocities of four zero volt metal lines of Fe I, Mn I, Cr I, Al I (e.g. 4375.9 A of Fe I) measured on EC2056 seem to show nearly the same value 27.6 ± 2.0 km s^{-1} as that of high-excitation C I lines 26.3 ± 2.0 km s^{-1} and the mean of all 63 lines, 27.6 km s^{-1}. This does not support the idea that the additional absorption comes from ejected or expanding cool gas. Usually during the deep minimum Na I *D* lines show blueshifted P Cygni absorption corresponding to −130 to −250 km s^{-1} (Rao 1981; Gaposchkin 1963).

From the polarimetric observations obtained during the light minima, and in particular the 1986 light minimum, Stanford *et al.* (1988) suggest that the dust ejection occurs in a preferred plane. One possibility they suggest for explaining such ejection is non-radial pulsations, which in the case of the $l=1$, $m=0$ mode could produce a bulge around the equator of the star in every pulsation cycle. The atmosphere above such a bulge is expected to be cooler than other parts of the atmosphere and dust formation is more likely to occur in the plane defined by the bulge.

The region of dust formation is not clear as yet, but the strong bands of C_2, CN and transient features most probably due to C_3 do indicate an intermediate phase leading to grain formation during the light minimum. The absence of the λ4050.5 feature during the light minimum indicates that most of the grain formation has already taken place and the intermediate molecules like C_3 cease to exist. Further detailed modelling is required to estimate various molecular abundances and their ratios in the R CrB atmosphere.

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