SOME SPECTROSCOPIC PROBLEMS OF CORONAE BOREALIS STARS *

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INTRODUCTION, PROPERTIES AND MEMBERSHIP:

I would like to bring to your attention some of the problems in understanding the nature of R Cor Bor stars, with some emphasis on spectroscopy. The study of these stars is important in two respects: 1) These are an abnormal sample of stars which are deficient in hydrogen and rich in carbon; thus they are of great interest in the study of stellar evolution. 2) Secondly they are supposedly making carbon dust in their atmosphere; thus a study would be important in understanding the physical conditions and processes of dust formation. In particular R CrB, being a hot star with $T_{\mathrm{eff}}=6000°\mathrm{K}$, presents an interesting example for dust to occur or being made in a hotter environment than is normally believed.

R CrB stars are a group of irregular variables which stay at maximum light for most of the time with only minor fluctuations (0.2 mag), but quite unpredicatably they decrease in light, somewhere between 2 to 7 magnitudes or more. Often the light curve is characterized by a rapid decline and a slow recovery with many hesitations and fluctuations.

At maximum light they look like F-G Ib supergiants or R stars with characteristic peculiarities emphasized by Bidelman (1953) and Herbig (1958) namely: the hydrogen lines and the G band of CH are weak or absent, C I lines and/or C_2 bands due to ^{12}C molecule are strong, but those due to ^{13}C are not.

Indeed, R CrB stars are one of the rarest group of variables per unit volume. Although some 35 objects have been listed in the General Catalogue of variable stars as belonging to this class, only a few objects have sufficient spectroscopic information to be considered as members of the group. Often the membership is assigned from the nature of the light curve alone, but spectroscopic confirmation is needed. It would be worthwhile to check R type stars which are not long period variables to find new members of this class.

The galactic distribution of these objects shows that they are in the plane and concentrated towards the galactic centre and probably belong to the old disc population. From this, Warner (1967) estimated the average mass to be $\sim 1\, m_{\odot}$. However, a few non-variable hydrogen deficient carbon (HDC) stars show a large dispersion in their space velocities (Warner 1967) and seem to belong to population II; thus a kinematical study of these objects would be worthwhile. From the members of the Large Magellanic cloud Feast (1972) estimated their M_V as -4 to -5.

SPECTRUM AT MAXIMUM LIGHT:

(a) The Line Spectrum and Abundances :—

Only a few members of this class have been studied in some detail at high dispersion (R CrB: Searle 1961, Keenan and Greenstein 1963; RY Sgr: Danziger 1965; XX Cam: Orlov and Rodriguez 1974). Therefore, most of the following discussion would be about R CrB, the better studied object of the group.

Berman (1935) was the first to analyse the spectrum of R CrB and show that carbon is enhanced and hydrogen is deficient. Except for these the line spectrum was found to be similar to γ Cyg (F8 Ib). Later Searle (1961) performed a differential curve of growth (COG) analysis relative to δ CMa (F8 Ia) with the lines in the blue and showed that the ratio C/Fe is 25 times that of δ CMa and hydrogen is deficient by a factor of 10^4 by number. Consequently, he suggested that the major constituent of the atmosphere is helium. Except for these, the rest of the elements seemed to show the solar abundances. By identifying He I λ 5876, Keenan and Greenstein (1963) confirmed the expectation that indeed He is the major constituent of the atmosphere. In their study, they compared the absorption line spectrum of α Per (F5 Ib) and R CrB from λλ 3800-8700 and identified some 250 C I lines in R CrB and showed that the line spectrum in both stars is very similar except for the lines of O and Sc, which were found to be enhanced in R CrB. Another interesting result of their study is that Li is found to be abundant in R CrB. Inspite of their detailed study, identifications are still lacking for many lines. This was followed by a study of RY gr by Danziger (1965) which showed essentially the same abundances as of R CrB except for Na, which was found to be enhanced by 0.6 in log relative to β Aqr (G0 Ib). This estimate rests on four lines including the two Na D lines. However, the D lines show blueshifted components at the time of light minimum (Alexander et al 1972) and in case of R CrB, Keenan and Greenstein found components even at maximum light which they interpreted as of interstellar origin. So it is better to avoid these two lines for further confirmation. Use could be made of lines in the red and near infrared (multiplets 4 and 5). Note that Warner (1967) also found Na to be enhanced in non-variable HDC stars. Again this depends on two weak lines in the blue. Danziger also found Li enhanced in RY Sgr.

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The evolutionary stage of these objects is not quite known although the abundance of ^{12}C and H-poorness suggests a late stage of stellar evolution. Observationally, there seems to be a correlation between [C/H] ratio and the abundance of [Li], which probably indicates mixing between surface layers and the interior (see table 1). Of course, this has to be established with other stars of the class on a uniform scale. As suggested by Warner (1967), use of the [C I] line at 8727 Å would give a better estimate of the carbon abundance.

TABLE 1

	R CrB	RY Sgr	HD 182040
[C/H]	1.1	1.4	$\geqslant 2.8$
[Li]*	4.1†	3.6	< 1.8††

[C/H] is from Searle (1961), Danziger (1965) and Warner (1967).

* [Li] is on the scale of Wallerstein and Conti (1969).

† [Li] in R CrB is estimted from the eq. width (0.22Å) given by Keenan and Greenstein (1963).

†† From Torres Peimbert and Wallerstein (1966).

One of the great puzzles about these stars is what happened to all the hydrogen. They show hydrogen deficiencies by a factor of 10^4 to 10^5 in number (Warner 1967). It has been suggested that the whole hydrogen envelope has been ejected by the star at some stage. But there is one HDC star, HD 148839 found by Warner, which shows a moderate hydrogen deficiency by a factor of 50 only (Warner 1967). If it is due to ejection it could not have been a sudden ejection of the whole envelope but rather a gradual one. The other explanation could be that the hydrogen has been consumed by the star itself.

(b) The Continuous Spectrum :—

Not only the line spectrum is similar to that of normal F-G supergiants except for the abnormalities mentioned, even the continuous spectrum seems to be very similar. The comparison of the energy distributions of γ Cyg and R CrB shows that the continuous opacity of both stars above the Balmer jump is comparable.

Myerscough (1968) computed an unblanketed model atmosphere of R CrB using Searle's abundances and matched the energy distribution in the near IR with T_{eff}=5800 °K, and g=0.5 cm sec^{-2}. However, the fit of the theoretical and the observational energy distributions deviates towards shorter wavelengths, which she explained as due to the line blanketing. Secondly, the atmospheric parameters obtained from COG are different from those of the calculated model, i.e. $T_{eff} \approx T_{ion}$=6500 °K (Searle 1961, Rao 1974) and log k (4500 Å)≈1.5. Another observational test which she proposed to obtain the effective gravity for a given T_{eff} is the decrement of $(3s)^1$ P edge at 3461 Å of C I. The scanner observations show much higher gravity g=10 cm sec.$^{-2}$. Thus it is not quite clear whether the line blanketing would explain the continuous spectrum, or some other opacity sources are needed.

SPECTRUM AT MINIMUM LIGHT :

The light variation of R CrB have been suggested by O'Keefe (1936) as due to the formation of a cloud of carbon dust at the time of the minimum, which obscures the star light. Thus, the flux received is a combination of the direct star light scattered through the dust cloud and the reemitted flux from the dust cloud. The detection of infared excess in these stars (Stein et al 1969; Lee and Feast 1969 ; Feast and Glass 1973; and Forrest 1974) seems to confirm this model.

Unlike the spectrum at maximum light, these stars show a curious emission line spectrum, first observed by Joy and Humason (1923) and was described in some detail by Herbig (1949, 1958) and Gaposchkin (1963) for the 1949 and 1960 minima of R CrB. There appears to be three kinds of spectra present at minimum. (1) A sharp emission line spectrum of predominently singly ionized metals, which is displaced to the blue by 3-10 km/sec from the absorption line spectrum (22-24 km/sec) at maximum. (2) A broad emission line spectrum of H and K lines of Ca II, Na D lines and λ 3889 of He I. The widths of these lines seem to indicate expansion velocities of 250 km/sec; in addition, the Na D lines show blue shifted absorption components of 275 km/sec (Gaposchkin 1963). (3) An absorption line spectrum similar to that at the maximum but 'veiled' or indistinct.

The study of RY Sgr by Alexander et al (1972) and SU Tau by Herbig (1958) shows that similar phenomenon also occurs in them at the time of the light minimum. But for these stars, none of the late type carbon stars of this group have been studied at minimum light.

The main problems concerning the spectrum at minimum light are : (1) How are the changes in emission line intensities related to the obscuration and reddening ; (2) The cause of the obliteration or veiling of the absorption line spectrum. To investigate these issues the spectrograms obtained by Dr. Herbig with Lick 120-inch telescope in the 1962 minimum were studied with the help of scanner energy distributions obtained in the 1972 and 74 minima of R CrB.

(a) Sharp Emission Lines :—

These emission lines become prominent at V=9.0, since a spectrogram obtained in 1963 at V=8.7 shows emission only in the cores of H and K lines of Ca II, whereas the first spectrogram in 1962, when the star was at V=9.3, shows a well developed emission line spectrum dominated by lines of Ti II, Sc II, Sr II, Fe II, Fe I etc.. These emissions are seen only in the lines with $\epsilon_{upper} \leqslant 5.6$ eV. The filling in of some lines and the appearence of the longward wing of underlying absorption features in some lines indicate that the emission lines are simply superposed on the absorption line spectrum.

At the time of the minimum, the continuum light gets reddened as could be seen from the scanner energy distributions and UBV photometry (Rao 1974). Unlike the continuum, the emission lines are not affected by the reddening. This is seen from the fact that the relative intensities of lines increase towards shorter wavelengths, i.e. the lines which are expected to have the same intensities show an increase with decreasing wavelength, e.g. Ti II λ4290 (RMT 41) and λ5188 (RMT 70) both have same $\varepsilon_{\text{upper}}$ (4.04, 3.95) and also the same log gf (– 1.16, – 1.15) but their relative intensities are 5 and 2 respectively on an arbitrary scale, when the star was at $V=10$. Herbig noted in the 1949 minimum that relatively high excitation lines (5.1 and 6.1) of Ti II (λ 3504, λ 3510) and Cr II (λ 3408, λ 3422) were present in UV but Fe II lines which have the same $\varepsilon_{\text{upper}}$ were absent in blue. Gaposchkin also noted similar trends in the 1960 minimum. In addition, UBV photometry of the 1962 and 1972 minima confirms this result (Rao 1974).

Saturation and self absorption seem to be present in some lines and decrease as the minimum progresses, e.g., the ratio of the lines of Sr II λ 4077 and La II λ 4086 both of which are resonance lines and have $\varepsilon_{\text{upper}}=3.0$ eV, was 3 at $V=9.3$; but at $V=11.8$ the ratio was 17.

As the minimum progresses, the level of excitation decreases and these emission lines decay by the time the star is on the recovery branch of the light curve. At least in the later phases of the 1972 minimum, the scanner fluxes at λ 4290 and λ 4395 show that the emission lines decay exponentially.

Since the emission line spectrum is strong when first observed and decays as the minimum progresses, the question arises whether it is present even at maximum light. An extrapolation of the exponential decrease of emission line intensities back to the maximum show that emission features could only be detectable in absorption lines with central depth $\approx$0.9. From similar considerations, Gaposchkin (1963) pointed out that Sc II λ 4246 should be observable as a central emission and in fact Keenan and Greenstein (1963) observed this as a double at maximum. Furthermore, Greenstein (1957) observed certain multiplets of Ti II, Fe II, Cr II which showed variable line doubling with separations less than 10 km/sec. Since the radial velocity of the sharp emission lines is only shifted by 3-10 km/sec from the maximum absorption line spectrum, this seems to be consistent with the idea that line doubling is due to the central emission. Thus the emission line spectrum can be properly regarded as a permanent feature of the spectrum.

To investigate the changes in the physical conditions of the emission line region, a curve of growth analysis under conditions of LTE (Aller 1954; Letfus 1961, 1964) was performed with the spectrograms obtained during the 1962 minimum. The results show that at $V=9.3$ the gas density $n=2\text{-}4\times10^{-12}$ cm^{-3}, $T_{\text{ex}}=5000$°K, $\xi=8$ km/sec and at $V=10.8$ we have $n=4\times10^{11}$ cm^{-3}, $T_{\text{ex}}=5000$°K, $\xi=15$ km/sec. Since these values are comparable to the gas densities obtained at maximum ($n=10^{15}$ cm^{-3}, $\xi=8$ km/sec), this indicates that the emission line region is not far above the stellar atmosphere at maximum. From the physical conditions at maximum, and by assuming mass and radius as 1 $m_\odot$ and 100 $R_\odot$, respectively, the scale height is obtained as 4.2×10^{10} cm So the gas density obtained at $V=9.3$ for the emission line region (chromosphere) is reached at 3.65 scale heights, showing that the chromosphere is close to the star.

(b) **Absorption Lines at Minimum :—**

At the time of the minimum the absorption spectrum gets veiled or becomes indistinct, until near minimum when only the strongest group of lines can be discerned as vague depressions in the continuum, first described by Herbig for the 1949 minimum and could be seen prominently in fig. 2 of Herbig (1968). Gaposchkin's study shows that the lines also have a redshift (compared to the maximum radial velocity) at the same time as this obliteration or veiling occurs. As mentioned before, the sharp emission occurs only for lines with $\varepsilon_{\text{upper}}$ less than 5.6eV only and the high excitation lines of C I, Mg II, etc. remain as absorption features. At minimum, the veiling occurs in all the lines irrespective of excitation potential or strength at maximum. This effect is not due to line emission and is shown from the fact that the equivalent widths of C I lines remain the same. The other possibility is that the broadening and redshifts of the absorption lines could result if the dust cloud responsible for the extinction also scatters the absorption line spectrum as it expands. To investigate this possibility the profiles of two C I lines λ 4770 an λ 4775 were studied on the spectrograms obtained in the 1962 minimum.

The computation of the profile is done with the assumption that the absorption line at maximum (when there is no dust cloud present) has a Gaussian profile. Now the star is assumed to be surrounded by a spherical dust shell expanding with a uniform velocity V_e, which only scatters the absorption line spectrum of the star. In a single scattering, as observed from the earth, a photon scattered from the volume element $d\sigma$ in the shell will be shifted such that (omitting terms of the order $(V_e/c)^2$)

$$\lambda = \lambda_0\left[1+\frac{V_e}{c}(1-\cos\theta)\right]$$

where θ is the angle between line of sight and the outward normal at $d\sigma$ from the centre of the star. Thus the line profile would be modified as a function of this Doppler shift and the scattering phase function (limb darkening was not considered) integrated over the extent of the cloud. In these calculations, it is assumed that the far half of the shell does not contribute. The scattering redshifts and the profiles were computed with Mie scattering phase functions for graphite particles of 500 Å radius and were compared with the observations.

The results show that in the initial stages of the minimum until $V=10.1$, there are no scattering redshifts present in the spectrum. The broadening of the lines, if attributable to turbulence, will give a velocity of 15 km/sec for the random motions. At later phase $V=10.1$ to $V=10.8$, the observed redshifts correspond to expansion velocities of 40 and 46 km/sec for the dust cloud. Note that at these phases, if the decrease in the gas density (already mentioned) in the emission line region is attributed to the expansion of dust clouds lying below the emission line region, then the calculated scale height indicates that the required expansion velocity is 20-25 km/sec. At a still later phase, $V=11.8$, the observed scattering redshift corresponds to 80 km/sec expansion velocity for the dust. The observed profiles, though more uncertain, are compatible with the computed profiles for the expansion velocities deduced from the measured radial velocities. Thus there seems to be an indication that the dust shell gets accelerated as the minimum progresses.

It is to be noted that the contribution for the scattering redshifts in the lines comes mainly from the parts of the clouds with $\theta \simeq 90°$, i.e. in certain minima, if the solid angle filled by the cloud is small and in the line of sight, no scattering redshifts and shallowing of the absorption lines is to be expected. In fact this seems to be the case with the 1972 minimum. The IR excesses observed at that time show that the solid angle filled in by the cloud is small $0.03 \times 4\pi$ (Forrest 1974). The spectrograms obtained by Herbig in the region of 8000 Å at two phases give radial velocities of 22 km/sec which agrees with the radial velocity at maximum and shows no scattering redshifts. On the otherhand in the 1974 minimum, when most of the front half of the star was filled by the dust envelope ($0.4 \times 4\pi$ from infrared excess—Forrest 1974), the expected redshifts were present in the spectrum at $V=11$ and even the lines look shallow on visual inspection. Thus it is seen that at certain minima the dust cloud distribution seems to be asymmetrical.

(c) **Broad Emission Lines** :—

The broad emission lines of H and K of Ca II, Na D lines and He I 3889 give evidence for gas ejection at a high velocity of 250 km/sec. Gaposchkin (1963) found blue shifted absorption components for Na D lines which give velocities of expansion of 275 km/sec and also showed that the widths of these lines correspond to such velocities. In the 1962 minimum, these blue shifted components of 130 km/sec were present in the first spectrograms obtained in this region at $V=10.0$, before the effect of dust expansion is seen in the spectrum.

MODEL :

Since there is increase in IR excess at the time of the light minimum and also the star gets reddened, it indicates that formation of dust occurs at the time of the minimum. As mentioned earlier the emission line region which is close to the star does not get reddened at least in the initial stages of the minimum. The main problem now is where does this formation of dust takes place. Most of the observations could be understood if (case 1) a cloud of gas is ejected in front of the star, which while expanding condenses at certain distance ($> 7 R_*$, Krishnaswamy 1972) and thereby occults only the stellar photosphere without obstructing the chromosphere (in the initial stages). Further expansion of the cloud results in the gradual obscuration of the chromosphere as well. Or, (case 2) a dust cloud forms below the region of emission lines.

The evidence for high velocity gas ejection is provided by the absorption components of Na D lines. At 200 km/sec, this gas shell reaches a distance of $7 R_*$ in 4 days. No spectroscopic information is available to establish whether these components were present prior to the descent to the minimum. But in case 1, if the dust forms from this gas, then dust velocities are expected to be much larger than the velocities actually obtained in 1962. Secondly, Forrest (1974) also inferred expansion velocities of 30 km/sec from the IR observations independently. A stronger objection to this model arises from the exact dimensions required for the cloud so that the chromosphere would remain unobscured. The solid angle subtended by a cloud (circular) with radius r_c at the star is $\pi r_c^2 / R^2 = 4 \pi \alpha$ where R is the star cloud distance and α is defined from infrared excess as $\alpha = F^{IR}_{ex}/F_*$; taking $r = R_*$ ($100 R_\odot$) and $R = 7 R_*$, the value of α is 0.005. But the infrared observations show that α is indeed greater than this value. Further the requirement that the cloud has to be the same at every minimum and for all R CrB stars seems to rule out this picture.

On the other hand, if the dust cloud formed below the region of emission lines (case 2), most of the observations could be explained. The main problem is then the physical one, namely, how the dust can form at temperatures which presumably are in the region of 5000°K. Another puzzle is the 900°K black body temperature of the dust from he IR observations.

It might be worthwhile to investigate theoretically the temperature structure of the atmosphere of R CrB to determine whether a temperature minimum could exist at the base of the chromosphere, where under special conditions particle condensation might be possible.

Apart from the problems mentioned in the text, the following suggestions for further work might be considered from the observational point of view :

1) Simultaneous observations of the progressive changes in emission line intensities and the obscuration during the light minimum. In the present study the continuum scans of 1972 and 1974 were used to analyse the spectra of 1962, thus it became necessary to assume that at a given V mag the emission line intensities are the same in all the three minima.

2) At present there is very little high dispersion spectroscopic material available for the recovery phase of the light curve. This would be valuable for a detailed study of the changes of the scattering redshifts of absorption lines, which would elucidate the motions of the dust envelope.

3) The source of excitation and mass loss rates of gas in the region where the broad emission lines originate is one of the problems which has not been studied adequately.

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