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Optical emission bands in the spectrum of the R CrB star V 854 Cen at minimum

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ABSTRACT

Several unidentified broad emission features, previously seen only in the spectrum of the nebulosity in the Red Rectangle, have been observed in a spectrum of the R CrB star V854 Cen taken in a deep minimum. Similarities and differences between the bands from the two sources are noted. The presence of the bands associated with an R CrB star may suggest that their carrier does not contain hydrogen atoms. Extended red emission seen from the Red Rectangle and probably associated with hydrogenated carbon grains is not present in the spectrum of V854 Cen.

Key words: circumstellar matter – stars: individual: V854 Cen – stars: variables: other – ISM: molecules.

1 INTRODUCTION

V854 Cen (=NSV 6708) is an R Coronae Borealis (R CrB) star. R CrB stars are noted for their hydrogen deficiencies, but V854 Cen shows strong Balmer lines at maximum light. R CrB stars are also noted for their rapid and unpredictable declines in brightness. V854 Cen undergoes frequent declines, and sometimes drops to $V \simeq 15.5$ from its maximum brightness of $V \simeq 7.3$. The star also possesses a large infrared excess, as is typical of R CrB stars. The spectrum seen at maximum light is typical of other R CrB stars such as R CrB and RY Sgr, except for the presence of strong Balmer lines and an overall weakness of atomic lines other than those of C I. The spectrum that emerges at deep minimum ($V \sim 15$) is quite different from that at maximum light. Our high-resolution spectroscopic study in the wavelength range 5480 to 7070 Å (Rao & Lambert 1993) showed mainly three distinct components in the spectrum at minimum: a continuum devoid of all photospheric lines, a collection of sharp emission lines of Sc II, Ti II, Y II and Ba II with a width (FWHM) of about 12 km s^{-1}, and broad emission (FWHM = 200–470 km s^{-1}) of [O I], [N II], [S II], Hα, Na D and C_2 Swan bands. Emission lines of Ca II and [C I] were also present.

In addition to these main features, several unidentified emission bands were also observed. The coincidence in wavelength of some of these with the emission bands in the Red Rectangle (Schmidt, Cohen & Margon 1980) was noted by Rao & Lambert (1993). The recent detailed investigation by Scarrott et al. (1992) of the emission bands in the Red Rectangle (RR) revealed many more similarities with the diffuse emission bands seen by us in V854 Cen, and indicates that the same carriers are present in both objects. In this paper, we present and discuss these emission bands in V854 Cen, which happens to be only the second object after the RR to show these bands in emission. The exciting stars are of similar effective temperatures: $T_{\rm eff} \simeq 7000$ K for V854 Cen (Lawson & Cottrell 1989) and 7500 K for HD 4179 of the Red Rectangle (Waelkens et al. 1992).

2 OBSERVATIONS

The details of the observations were given in Rao & Lambert (1993). Briefly, spectra were obtained in the range 5480–7070 Å with Cerro Tololo Inter-American Observatory's 4-m telescope and the Cassegrain echelle spectrograph at a resolution of 0.34 Å (FWHM) on 1992 May 21 and 22. The brightness of the star was $V \sim 15$. An observation of an early-type star was used to correct for the blaze function of the echelle. The flux calibration of the spectrum was carried out via spectrophotometry performed on CTIO's 1.0- and 1.5-m telescopes.

Several prominent broad emission lines in the V854 Cen minimum spectrum could not be identified by Rao & Lambert (1993), and are listed in Table 1. The peak wavelengths are definable to about ±1 Å and the equivalent widths to about ±10–15 per cent. All but one of the features were also listed by Rao & Lambert (1993). Most of these unidentified lines are shown in Figs 1 to 3. There is also an

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unidentified emission feature at 8329 Å in the low-resolution (~10 Å) spectrum. The 'broad emission bump 200 Å wide lying under the Na I D lines' seen by Whitney et al. (1992) in their low-resolution spectrum ($\Delta\lambda \simeq 14$ Å) at minimum might correspond to the blend of these unidentified features extending from about 5760 to 5910 Å.

3 A COMPARISON WITH THE RED RECTANGLE

In Table 1 we also list the wavelengths of the sharp emission bands observed in the Red Rectangle by Scarrott et al. (1992) in the interval 5700–6650 Å. All of the strong features in the RR also occur in V854 Cen. However, the extended red emission (ERE) found in the RR and other reflection nebulae is not present in V854 Cen. Scarrott et al. obtained spectra at a resolution of 1 Å at different offset distances from the central star. The bands change shape with offset distance in a symmetrical manner on either side of the central star. These changes were attributed to a decrease of the excitation temperature of the molecules responsible for the emission. This suggestion presumes that the widths of the bands in the RR are controlled by the excitation temperatures of the carriers and not by mass motions of the gas hosting the carriers. The width of a band in the RR spectrum decreased from about 7 Å near to the central star to about 3 Å at larger offsets (i.e. in cooler conditions). The peak of each band (λ_{max}) shifts towards shorter wavelengths at larger offsets. The peak wavelength changes by ~5 Å over the range of offsets covered. The widths of the emission features in V854 Cen are comparable to (or even smaller than) the features in the RR: e.g. λ5800 has a FWHM of ~10 Å in the RR (Fig. 3, spectrum 36 of Scarrott et al.) and 9.1 Å in V854 Cen; λ5828 has a FWHM of 11.4 Å in V854 Cen and ≃15 Å in the RR. The similarity of the emission widths for the two objects stands in sharp contrast to their Na I and Hα lines. In V854 Cen the Na I and Hα and forbidden lines are broadened by ~250–450 km s^{-1}, but in the RR Na I and Hα are narrow emission lines of widths less than 35 km s^{-1} (Warren-Smith, Scarrott & Murdin 1981). The large widths of Na I, Hα and the forbidden lines in V854 Cen are attributed to mass motions (expansion of a nebula?). Since the unidentified emission bands are much sharper, we presume that they are emitted by regions that do not partake in the gas flows emitting the very broad lines. We cannot, however, eliminate the possibility that the widths of the bands in part reflect flow velocities.

The peak wavelengths of the bands in V854 Cen are shifted redward by 2–3 Å relative to the mean values given by Scarrott et al. in the RR, and the widths of the 5800-, 5827- and 5855-Å bands in V854 Cen are comparable to

Table 1. Comparison of band properties.

V854 Cen			R R		DIB[c]
λ_{max} (Å)	Eq-Width (Å)	F_λ[a]	λ_{max} (Å)	Strength[b]	λ (Å)
5772	0.95	1.8			(5780)
5800	0.65	1.27	5800	V. Strong R	5797
5829	1.54	3.1	5827	Moderate S	
5855	0.50	1.0	5853	Strong R	5850
			6380	Moderate S	6376/79
6618[d]	0.54	1.2	6615	Strong R	6613
6774[d]	0.3	1.0			(6770)
6997	0.29	0.8			6993

[a]Flux is given in units of 10^{-15} erg cm^{-2} s^{-1}. [b]R≡red degraded, S=symmetrical. [c]Herbig (1975); Herbig (1988); Herbig & Soderblom (1982). [d]$\lambda\lambda$6618 and 6774 features show some structure in their profiles.

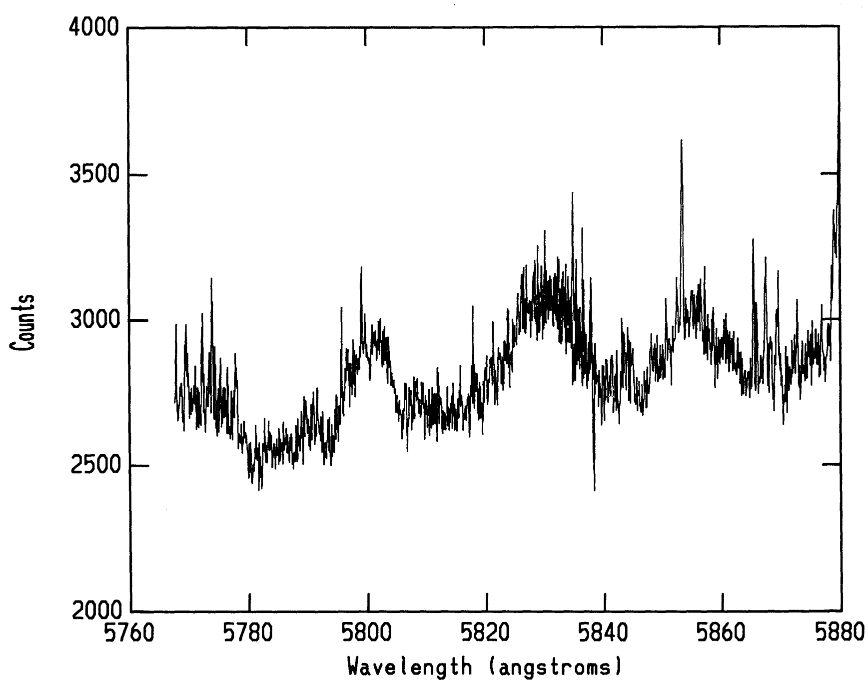

Figure 1. The spectrum of V854 Cen in a deep minimum, showing unidentified emission features at 5772, 5800, 5829 and 5855 Å. The sharp emission line at 5853 Å is due to Ba II.

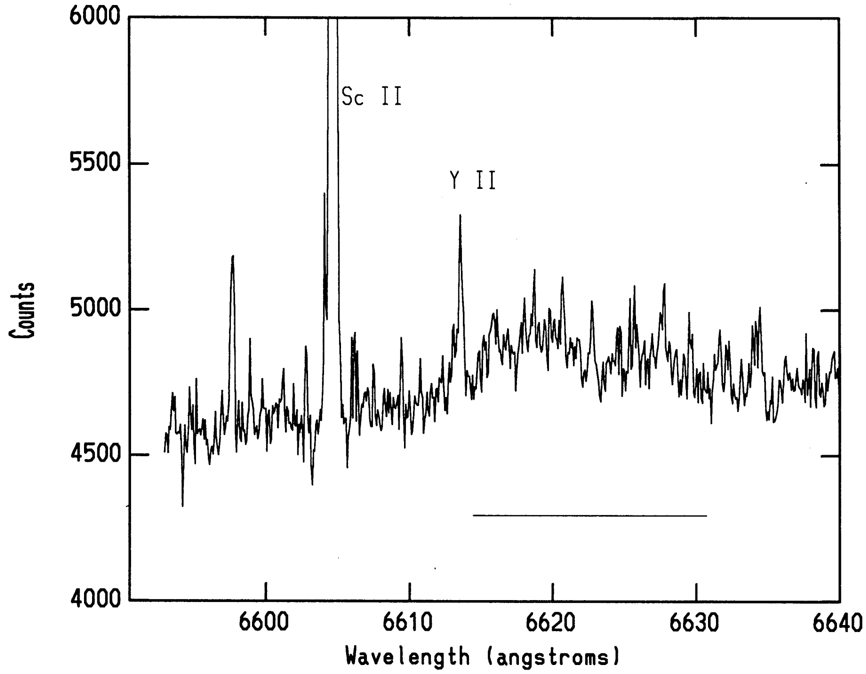

Figure 2. The spectrum of V854 Cen in a deep minimum showing an unidentified emission feature at 6618 Å. The bar shows the presumed width of the 6618-Å feature. Sharp emission lines due to Sc II and Y II are identified.

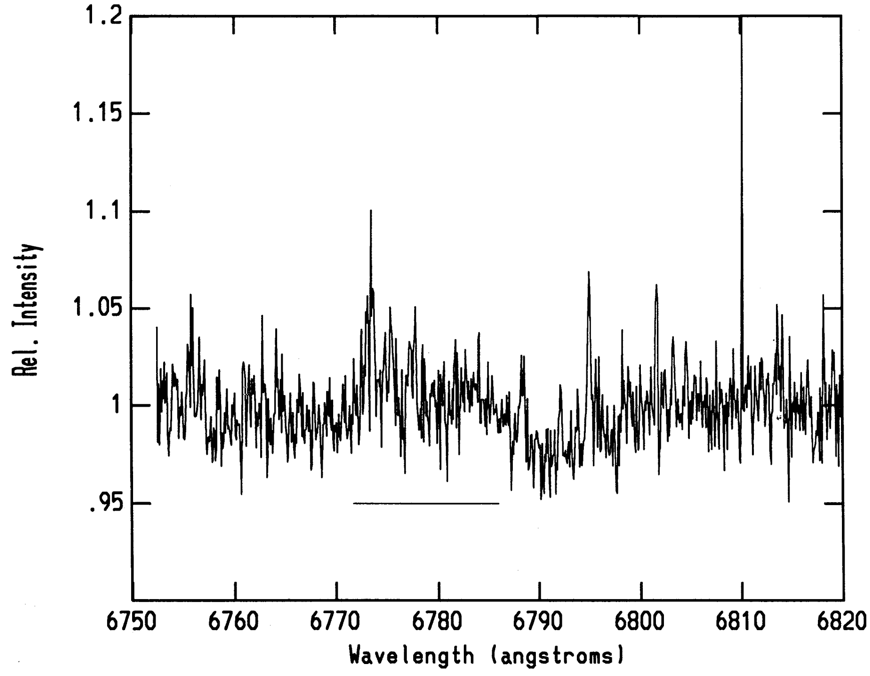

Figure 3. The spectrum of V854 Cen in a deep minimum showing an unidentified emission feature at 6774 Å. The bar shows the presumed width of the emission feature. The weak sharp emission line at 6795 Å is due to Sc II.

those in the RR at the position closest to the central star. Both of these features suggest that the bands in V854 Cen are at the same temperature or slightly hotter relative to the bands displayed in the RR.

Although the wavelengths and widths are similar in both objects, the relative intensities of the bands are different. The strongest feature in the RR is $\lambda5800$, followed by $\lambda\lambda5853$, 6615, 5827 and 6380. The $\lambda6380$ feature is of moderate strength. In V854 Cen the strongest feature is $\lambda5829$, followed by $\lambda\lambda5800$ and 5855. $\lambda6380$ is very weak (if present). However, as can be seen in the spectra of the RR displayed by Scarrott et al. (their fig. 2), the relative ratio of the strengths of $\lambda5827/\lambda5853$ and $\lambda5827/\lambda5800$ is smallest in the spectrum taken closest to the central star. This trend suggests too that the V854 Cen spectrum shows hotter material than does that of the RR.

Another feature distinguishing V854 Cen from the RR is the shape of the bands of $\lambda\lambda$5800 and 5855: both show symmetrical profiles in V854 Cen, but their profiles in the RR are obviously red-degraded.

Scarrott et al. established a correspondence of the strong $\lambda\lambda$5800, 5855, 6380 and 6615 emission features in the RR with one family of diffuse interstellar bands (DIBs), i.e. $\lambda\lambda$5797, 5850, 6377/79 and 6613 (Krełowski & Walker 1987). The same bands (except λ6380) are also strong in V854 Cen. A further search of the V854 Cen spectrum for emission bands corresponding to the other DIBs revealed a weak feature at λ6997, which might correspond to the DIB at λ6993 (Herbig and Soderblom 1982). The feature at λ5772 Å could possibly correspond to the DIB at λ5780, but this feature is not prominent in the RR. We searched unsuccessfully for all of these unidentified bands in absorption in a spectrum taken in 1989 when V854 Cen was at maximum.

4 DISCUSSION

As discussed by Scarrott et al. (1992), these emission bands in spectra of the RR have the appearance of electronic transitions of gas-phase large molecules, such that a band consists of many unresolved rotational lines. Several workers (Danks & Lambert 1976; Douglas 1977; Smith, Snow & York 1977; Snow & Seab 1991) have suggested that large molecules may be responsible for the DIBs. Molecular origins of the emission features in the RR were explored by Schmidt et al. (1980): the possible candidates considered include C_3 (see further discussion by Warren-Smith et al. 1981) and carbon chain molecules. Based on suggestions by Fossey (1991) and Sarre (1991), Scarrott et al. convincingly showed that the $\lambda\lambda$5797 and 5850 features, present in DIBs (in absorption) as well as in the RR (in emission), arise from the same carrier, although the other members of the same DIB family $\lambda\lambda$6376/6379 and 6614 bands may originate in a different species. The feature at λ5772 seen in V854 Cen may correspond to the DIB λ5780, but the other members of the same DIB family (Krełowski & Walker 1987) at $\lambda\lambda$6196, 6203, 6269 and 6284 Å are not present in emission in either the RR or V854 Cen. The profiles of $\lambda\lambda$5772, 5795 and 5850 in V854 Cen are much more symmetrical than the absorption profiles of these DIBs.

The question of whether the same species at different temperatures can account for both DIB and RR emissions has been explored by Scarrott et al. (1992) for C_{60} molecules and by Cossart-Magos & Leach (1990) for PAH molecules for the band at λ5797. Scarrott et al. showed a fair match of the observed profiles with the computed ones at 40 K (DIB) and 170–450 K (RR) for a C_{60} molecule with a 3 per cent reduction in the rotational constant on electronic excitation. However, Hare & Kroto (1992) indicated that the neutral C_{60} might not contribute any optical features, and they suggested C_{60} M ionized complexes, where M is an abundant metal atom like Ca or Na. Detailed spectroscopic identification from the laboratory is required to confirm these suggestions. It might be worth noting that Goeres & Sedlmayr (1992) showed that small amounts of C_{60} (Buckminsterfullerene) are likely to form in the ejecta of envelopes of R CrB stars. It has been suggested that ionized polycyclic aromatic hydrocarbons (PAHs), and in particular the ionized PAH naphthalene ($C_{10}H_8^+$), could produce features in the visible region corresponding to some of the DIBs (Salama & Allamandola 1992). There are two emission features ($\lambda\lambda$5784 and 5848, and perhaps λ6741) in V854 Cen whose wavelengths possibly coincide with features attributed to naphthalene. The computed rotational contours shown by Cossart-Magos & Leach (1990) show structures in the band profiles which are not observed in either absorption in DIBs or the emission from V854 Cen and the RR. Tarafdar et al. (1992) showed from theoretical computations that the carbon cluster C_7 could produce features corresponding to several DIBs and other bands. Some of their predicted features may correspond to unidentified emission bands in V854 Cen.

These various proposals concerning the carriers of the unidentified emission bands all feature molecules containing several carbon atoms. These proposals are not in conflict with the presence of the bands in V854 Cen. The photosphere of the star, the likely source of gas in the circumstellar regions, is carbon-rich (i.e. carbon is more abundant than oxygen) and, in probable contrast to the RR, hydrogen-poor and helium-rich. Strong C_2 Swan bands, the possible presence of C_3 emission at 4050 Å (Rao & Lambert 1993) and the CN band at 3883 Å (Kilkenny, private communication) show that carbon molecules are contributing to the spectrum. Our preliminary abundance analysis also shows that the photosphere of V854 Cen is metal-poor by perhaps a factor of 10 relative to the Sun's metallicity.

By examining potential environments of differing composition, it may be possible to constrain the conditions needed for the formation (and excitation) of the molecules providing the unidentified emission bands. Do the molecules only form in carbon-rich environments? It is generally assumed that HD 44179, the central star of the RR, is carbon-rich because the infrared emission features at 3.34, 7.7 and 11.3 μm are present in the spectrum of the RR with greater intensity [see Cohen et al. (1986, 1989) for the relations between the intensity of these bands and the C/O (also C/H and (C–O)/H ratio of the emitting gas]. Leinert & Haus (1989) suggested that the C-rich gas in the circumstellar environment of the RR may come from an unseen carbon-rich companion. An analysis of the photospheric spectrum of HD 44179 (Waelkens et al. 1992) suggests that the C/O ratio may be greater than unity but not by a large margin.

One clear difference between V854 Cen and the RR may be linked to differences in chemical composition. The extended red emission seen from the RR and many other reflection nebulae is not present in our spectrum of V854 Cen. Witt & Schild (1988) attributed the emission to hydrogenated carbon grains. Since V854 Cen is H-poor, these grains are likely to be in short supply, as is apparently the case. By the same token, the carriers of the optical emission bands possibly do not contain hydrogen atoms. Of course, a low abundance of the carriers may be offset by a higher efficiency in their excitation.

5 CONCLUDING REMARKS

Prior to this report on V854 Cen at a deep minimum, the optical emission bands were unique to the Red Rectangle. Scarrott et al. remarked that 'the uniqueness of the Red Rectangle only results from the fact that the conditions of temperature, density and ultraviolet illumination are optimum in this object and that the abundance of the particular species of molecule is high'. V854 Cen is now the second object to exhibit these unidentified bands. The presence of these features in V854 Cen suggests that hydrogen-deficient stars might be one of the contributors of the carriers of these bands to the interstellar medium. Since Scarrott et al. (1992) showed that there is a correspondence between the carrier(s) of the unidentified bands and one family of DIBs, continued searches for unidentified bands may lead finally to identification of the carriers of the DIBs.

In particular, spectra of the most H-poor of the R CrB stars should be acquired when the stars are at minimum light. If the unidentified bands are seen, one may suppose that the carrier does not contain hydrogen. V854 Cen, and other R CrB stars, should be observed at minimum at high spectral resolution over a greater wavelength range to search for additional unidentified bands. If the C_2 molecular gas and the carrier of these unidentified emission features co-exist, then the study of the C_2 Swan bands will provide information about the physical conditions necessary to produce the emissions.

It is also important to look for spectral features in infrared spectra of V854 Cen and other R CrB stars. The 3.38-, 7.7- and 11.3-μm emissions widely attributed to PAHs should be absent from spectra of the most H-deficient stars. The *IRAS* spectrum (1986) of V854 Cen may show 11.3-μm emission, but the published spectrum is of rather low quality. Emission from carbon-rich material in several possible forms (graphite, amorphous flakes, C_{60}) may be expected.

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REFERENCES

Cohen M., Allamandola L., Tielens A. G. G. M., Bregman J., Simpson J. P., Witteborn F. C., Wooden D., Rank D., 1986, ApJ, 302, 737
Cohen M., Tielens A. G. G. M., Bregman J., Witteborn F. C., Rank D. M., Allamandola L. J., Wooden D. H., de Muizen M., 1989, ApJ, 341, 246
Cossart-Magos C., Leach S., 1990, A&A, 233, 559
Danks A. C., Lambert D. L., 1976, MNRAS, 171, 571
Douglas A. E., 1977, Nat, 269, 130
Fossey S. J., 1991, Nat, 353, 393
Goeres A., Sedlmayr E., 1992, A&A, 265, 216
Hare J. P., Kroto H. W., 1992, in Singh P. D., ed., Proc. IAU Symp. 150, Astrochemistry of Cosmic Phenomena. Kluwer, Dordrecht, p. 47
Herbig G. H., 1975, ApJ, 196, 129
Herbig G. H., 1988, ApJ, 331, 999
Herbig G. H., Soderblom D. R., 1982, ApJ, 252, 610
IRAS Science Team, 1986, A&AS, 65, 607
Krełowski J., Walker G. A. H., 1987, ApJ, 312, 860
Lawson P. A., Cottrell P. L., 1989, MNRAS, 240, 689
Leinert C., Haas M., 1989, A&A, 221, 110
Rao N. K., Lambert D. L., 1993, AJ, 105, 1915
Salama F., Allamandola L. J., 1992, ApJ, 395, 301
Sarre P. J., 1991, Nat, 351, 356
Scarrott S. M., Watkin S., Miles J. R., Sarre P. J., 1992, MNRAS, 255, 11P
Schmidt G. D., Cohen M., Margon B., 1980, ApJ, 239, L133
Smith W. H., Snow T. P., York D. G., 1977, ApJ, 218, 124
Snow T. P., Seab C. G., 1991, ApJ, 382, 189
Tarafdar S. P., Krishna Swamy K. S., Badrinathan C., Mathur D., 1992, in Singh P. D., ed., Proc. IAU Symp. 150, Astrochemistry of Cosmic Phenomena. Kluwer, Dordrecht, p. 123
Waelkens C., Van Winckel H., Trams N. R., Waters L. B. F. M., 1992, A&A, 256, L15
Warren-Smith R. F., Scarrott S. M., Murdin P., 1981, Nat, 292, 317
Whitney B. A., Clayton G. C., Schulte-Ladbeck R. E., Meade M. R., 1992, AJ, 103, 1652
Witt A. N., Schild R. E., 1988, ApJ, 325, 837