High-resolution spectroscopy of V854 Cen in decline – Absorption and emission lines of C\textsubscript{2} molecules

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ABSTRACT

High-resolution optical spectra of the R Coronae Borealis (RCB) star V854 Centauri in the early stages of a decline show, in addition to the features reported for other RCBs in decline, narrow absorption lines from the C\textsubscript{2} Phillips system. The low rotational temperature, $T_\text{rot} = 1150$K, of the C\textsubscript{2} ground electronic state suggests the cold gas is associated with the developing shroud of carbon dust. These absorption lines were not seen at a fainter magnitude on the rise from minimum light nor at maximum light. This is the first detection of cold gas around a RCB star.

Key words: Star: individual: V854 Cen: variables: other

1 INTRODUCTION

R Coronae Borealis stars are H-poor F-G type supergiants that decline in brightness unpredictably by up to 8 magnitudes and remain below their normal brightness for several weeks to months. It is generally accepted that these declines are due to formation of a cloud of carbon soot that obscures the stellar photosphere. Unanswered questions remain: ‘What triggers cloud formation?’ and ‘Where does the soot form?’ High-resolution spectroscopic monitoring of RCBs from maximum light into decline will likely be necessary to refine schematic ideas into answers that are accorded widespread acceptance. We report the first detection of cool gas ($T \approx 1100$K) during the early decline of a RCB star and, hence, evidence for a site of soot formation. Cold dust is, of course, known around RCBs through detection of an infrared excess.

The RCB in question is V854 Cen, which at maximum light is the third brightest RCB variable after R CrB and RY Sgr. V854 Cen is presently the most variable of all Galactic RCBs. Despite the combination of favorable apparent magnitude and propensity to fade, there is a dearth of high-quality spectroscopic observations of this star in decline. The sole report of a high-resolution optical spectrum covering a broad bandpass in a deep decline is that by Rao & Lambert (1993) taken when the star had faded by about 8 mag. Low resolution spectra are described by Kilkenny & Marang (1989) and spectropolarimetric observations are discussed by Whitney et al. (1992). Spectra at high-resolution at maximum light were used by Asplund et al (1998) for their abundance analysis that confirmed that V854 Cen has a somewhat unusual composition among the RCBs for which abundance anomalies are a \textit{sine qua non}. In particular, V854 Cen, although hydrogen-poor relative to normal stars, is the most hydrogen-rich RCB by a clear margin. Despite limited temporal coverage, our new spectra of V854 Cen in decline provide a novel result – the detection of cold C\textsubscript{2} gas. Our spectra otherwise closely resemble those of the RCBs extensively studied in decline: R CrB (Rao et al. 1999) and RY Sgr (Alexander et al. 1972). This concordance, which suggests that RCBs have a common general structure of their upper atmospheres and circumstellar regions, is briefly demonstrated here but we focus on the novel lines of the C\textsubscript{2} molecule.

2 OBSERVATIONS

V854 Cen was observed on four occasions from the W.J. McDonald Observatory with the 2.7m Harlan J. Smith reflector and the 2d\textit{coudé} spectrograph (Tull et al. 1995). Details of the observations are given in Table 1. Figure 1 shows the light curve and the epochs of our spectra. The first two spectra at effectively the same epoch were taken when the star was at $V \approx 10.3$ about 55 days after the onset of a decline that saw the star fade to $V \approx 13.6$ by 1998 late-May. We reobserved the star on 1998 June 6 at $V \approx 11.7$ in its recovery to maximum brightness, and again on 1999 February 10 when the star had returned to maximum brightness. Observations by amateur observers show that the recovery from the deep decline in mid-1998 to maximum brightness in early 1999 was rapid, unbroken by subsidiary declines, and faster than the fall from maximum to minimum brightness which may have been interrupted by brief halts.
Table 1. Spectroscopic observations of V854 Centauri.

| Date       | XJD   | V    | S/N | Phase |
|------------|-------|------|-----|-------|
| 1998 April | 911.887 | 10.3 | 69  | 81.227 |
| 1998 April | 913.832 | 10.3 | 53  | 81.272 |
| 1998 June  | 970.679 | 11.7 | 61  | 82.587 |
| 1999 Feb   | 1219.988 | 7.3  | 149 | 88.354 |

* XJD = JD - 245000.0
* S/N ratio in continuum near 6560Å.
* Pulsation phase from Lawson et al.’s (1999) ephemeris where zero phase is light maximum.

Figure 1. The lightcurve for V854 Cen from early 1998 to early 1999. Dots refer to V magnitudes from Lawson et al. (1999), open squares and dashes are visual estimates from the AAVSO. The Julian dates of our observations are indicated by arrows.

The cross-dispersed echelle spectra are at a resolving power of 60,000 with nominal coverage from 3800Å to 10200Å. Echelle orders are incompletely captured on the CCD for wavelengths longward of 5500Å. In addition, the star’s southerly declination (Dec. = -39°) and the observatory’s northerly latitude (Lat. = 31°) result in severe atmospheric dispersion and loss of signal in the blue such that the spectra are not useable for wavelengths shorter than about 4100Å.

3 V854 CENTAURI IN DECLINE

Well-observed RCBs in decline – R CrB and RYSgr – show common spectral characteristics that are shared with V854 Cen. As a star fades, the first prominent addition to its optical spectrum are two sets of sharp emission lines: E1 (Alexander et al. 1972) or ‘transient’ (Rao et al. 1999) appear shortly after onset of a decline and disappear after a couple of weeks, and E2 or ‘permanent’ lines are prominent for a longer period and may be present in some or all declines at all times, even at maximum light (Lambert, Rao, & Giridhar 1990a). A mark of E1 lines is that they include high-excitation lines (C i, O i, and Si ii, for example) not found among E2 lines. Singly-ionised metals (e.g., Ti ii and Fe ii) are prominent contributors of E1 and E2 lines. The E1 and E2 lines are sharp (FWHM ∼ 14 km s⁻¹ in R CrB).

In deep declines, a few broad emission lines are seen with FWHM ∼ 300 km s⁻¹ with the Na D being the strongest. In our spectra of V 854 Cen, E1 lines, especially C i lines, are present in 1998 April: 46 C i lines from 6400Å to 8800Å give a velocity of -16.7 ± 2.8 km s⁻¹. Emission had gone by 1998 June with the same lines appearing in absorption at a velocity of -24.0 ± 2.4 km s⁻¹ which is the (out-of-decline) mean velocity of -25 km s⁻¹ that is maintained to about 2 km s⁻¹ as the star undergoes small semi-regular brightness variations (Lawson & Cottrell 1989). The velocity of infall of the C i emission lines is similar to that seen for R CrB (Rao et al. 1999). Lines of higher excitation such as the N i lines beyond 8000Å also appear affected by emission, i.e., the N i 8216Å line has an equivalent width of 59 mÅ and a FWHM of 0.36Å in April but its normal values, as in the 1999 February spectrum, are 164 mÅ and 0.69Å, respectively. It seems probable that emission has reduced the equivalent width, narrowed the line, and shifted the apparent absorption velocity to the blue with the mean absorption velocity at -34 ± 2 km s⁻¹ in 1998 April. Some C i emission lines show P Cygni profiles with absorption also at -34 km s⁻¹. Emission from E1 and E2 lines affects almost all photospheric lines in 1998 April. With the decay of E1 lines, the photospheric velocity is measureable from the 1998 June spectrum: the result -27 ± 1 km s⁻¹ is consistent with the systemic velocity. Lines of low and high excitation potential are at the systemic velocity on the 1999 February spectrum.

The E2 lines on the 1998 April and June spectra are slightly blue-shifted with respect to the mean photospheric velocity. The peak velocity which is unchanged between April and June is -30 ±1 km s⁻¹ corresponding to a blue shift of about 5 km s⁻¹, a typical value for the E2 lines of R CrB and RYSgr. The degree of excitation appears to be similar to that of R CrB in its 1995-1996 decline, and the line widths are also similar. The line fluxes dropped by about a factor of 30 from 1998 April to June, as the V flux dropped by a factor of only 4. This contrasts with the 1995-1996 decline of R CrB when the line fluxes dropped by less than the V magnitude.

The only detectable broad lines are the NaD lines. Other broad lines reported by Rao & Lambert (1993) are not present. We attribute their absence to the fact that our observations were taken at V = 11.7 (and 10.3) but the spectrum on which our earlier report was based was obtained when the star was about 3 magnitudes fainter. Similarly, R CrB’s broad lines appeared only in the deepest part of its decline.

Low-excitation lines of neutral metals are in absorption without discernible emission but with their weak absorption red-shifted relative to the systemic velocity: the mean velocity of +15 ± 2 km s⁻¹ from 7 lines on the 1998 April spectra implies infall at 40 km s⁻¹ relative to the photosphere. Similar red-shifted lines were seen in R CrB. This red-shifted absorption, which is also clearly seen in the red wing of prominent sharp (blue-shifted) emission lines, is unlikely to be the residual of the photospheric line (assumed...
to be at the systemic velocity) because the red-shifted absorption occurs outside the normal photospheric profile and many lines lack accompanying emission. The fact that the red-shifted absorption appears in lines of different excitation potentials indicates that the responsible gas is warm. By 1998 June, the same lines were at $-13 \pm 2$ km s$^{-1}$ and at the systemic velocity (i.e., photospheric in origin) by 1999 February.

These snapshots of V 854 Cen’s spectrum suggest its decline from onset to beyond minimum light largely behaved similarly to R CrB’s 1995-1996 decline. There is one exciting novel feature revealed for V854 Cen.

### 4 C$_2$ SWAN AND PHILLIPS SYSTEM LINES

Previous detections of C$_2$ in spectra of RCBs are for the Swan system which provides photospheric absorption lines at maximum light in all but the hottest RCBs, and sharp and broad emission lines in decline spectra (Rao & Lambert 1993; Rao et al. 1999). Swan photospheric and E2 lines are seen here. The novel feature is the detection of low excitation (non-photospheric) Phillips lines in absorption.

The Phillips system’s lower state is the C$_2$ molecule’s ground state ($X^1\Sigma^+ \text{g}$, Ballik & Ramsay 1963; Huber & Herzberg 1979) and its upper state ($A^1\Pi \text{u}$) has the excitation energy $T_e = 8391$ cm$^{-1}$. The Swan system’s lower level is the lowest and very low-lying triplet state ($a^3\Pi \text{u}$) with $T_e = 716$ cm$^{-1}$ and the upper state ($d^3\Pi \text{g}$) is at $T_e = 20022$ cm$^{-1}$. Other low-lying states exist but no other band systems from the ground or low-lying states provide lines in our bandpass. Radiative transitions between singlet and triplet states occur with a low transition probability relative to the Phillips singlet-singlet and Swan triplet-triplet transitions.

Resolved rotational structure in the Swan system 0-0 band is shown in Figure 2. The velocity, as measured from clean 0-0 lines is -27 km s$^{-1}$ which is that of the E2 sharp emission atomic lines. The line width, which is slightly greater than the instrumental resolution, is also equal to that of E2 atomic lines. The rotational temperature estimated following Lambert et al. (1990b) is $T_{\text{rot}} = 4625 \pm 300$K (see Figure 3). Many bands from the $\Delta v = 0, \pm 1$, and +2 sequences are present. Semi-quantitative comparisons of the band profiles in the $\Delta v = +1$ sequence with predicted profiles (Lambert & Danks 1983) indicate a vibrational temperature near 5000K and, hence, likely equal to the rotational temperature. Rao & Lambert (1993 - see also Rao et al. 1999 for R CrB) in a deeper decline found the Swan lines to be broad but in our spectra any broad component must be very weak.

Weak absorption lines identified as Phillips system lines are present on the 1998 April spectra but absent from the 1998 June spectrum. Figure 4 shows a portion of the 2-0 band and includes a spectrum of the post-AGB star IRAS 22223+4327 in which circumstellar C$_2$ lines are strong. Many lines from the 2-0 and 3-0 bands were detected in V854 Cen with equivalent widths of up to 50 mÅ. A search for 3-1 and 4-1 lines was unsuccessful; this is not surprising given the low excitation temperature found from the detected lines. No search was made for either 1-0 or 4-0 lines. Rest wavelengths from Bakker et al. (1997) give the radial velocity of $-30.4 \pm 1.3$ km s$^{-1}$ from 15 lines, i.e., a small expansion velocity relative to the systemic velocity of -25 km s$^{-1}$. The velocity differs considerably from that (+15 km s$^{-1}$) of the red-shifted absorption component of low-excitation atomic lines. In contrast to photospheric lines, the C$_2$ absorption lines are not resolved. Boltzmann plots for 2-0 and 3-0 lines give a mean rotational temperature of $T_{\text{rot}} = 1150 \pm 70$K from levels $J'' = 4$ to 28. We interpret this as a close approximation to the gas kinetic temperature. If, as occurs in interstellar diffuse clouds, the C$_2$ molecule’s
excitation is greatly influenced by radiative pumping in the 
Phillips bands (and $X^{1}\Sigma_{g}^{+} \leftrightarrow a^{3}\Pi_{u}$ radiative transitions), 
the Boltzmann plot is expected to be curved with lowest 
rotational levels giving a temperature close to the kinetic 
temperature and higher levels a higher temperature dependent 
on the ratio of the gas density and the photon flux in the 
near-infrared, for example, the ground state populations 
for $\zeta$ Oph’s diffuse clouds give $T_{\text{rot}} \simeq 40$K from the lowest 
levels and 785K from levels $J'' \simeq 20$ (Lambert, Sheffer & 
Federman 1995). A linear Boltzmann plot, as here, suggests 
that the observed levels may be in equilibrium with the gas, 
i.e., our $C_{2}$ molecules are in gas at a temperature below that 
at which carbon dust grains form, and the molecules may 
well be mixed in with the fresh dust. The molecular column 
density is about $2 \times 10^{15}$ cm$^{-2}$.

Five questions arise directly from these observations of 
$C_{2}$ lines: Why is an absorption component not seen in the $C_{2}$ 
Swan lines? Why is an emission component not seen in the $C_{2}$ 
Phillips lines? How are the Swan emission lines excited? 
Where is the emitting gas? Where is the cold absorbing gas?

The apparent absence of Swan absorption lines is easily 
explained. In the weak-line limit, the equivalent width $W \propto f \lambda^{2} N L$ where $f$ and $\lambda$ are the line's oscillator strength and 
wavelength respectively and $NL$ is the column density of 
molecules in the lower level of the transition. If the column 
densities in the lowest singlet and triplet states are equal, the 
Swan system lines are favored by a factor of about 7 with the 
system's greater $f$-value being a major factor (Grevesse et 
al. 1991; Bakker & Lambert 1998) but considering that the 
Phillips absorption lines are at almost the same velocity as 
the Swan emission lines ($-30$ km s$^{-1}$ versus $-27$ km s$^{-1}$), we 
suppose that the Swan absorption lines are masked by the 
strong emission lines. A large increase in the column density 
of the lowest triplet state relative to the ground triplet state 
would be required to provide detectable absorption.

A plausible explanation may be offered for the absence 
of Phillips emission lines. An approximate flux calibration 
of our spectrum gives the detection limit for a sharp Phillips 
line at about 0.2 that of a single sharp Swan line. The 
predicted relative fluxes in Swan and Phillips lines depends 
on the assumed mode of excitation. If the molecule is in 
thermal equilibrium at the measured $T_{\text{rot}} = 4625$K, it is 
readily shown that the flux in a Phillips 2-0 line is about 
15% that of the Swan 0-0 of a similar $J$-value in the event 
that reddening may be neglected, i.e., the line would not 
appear in emission in our spectrum. The great difference in 
the $f$-values of the 0-0 Swan band and the 2-0 Phillips band 
is a major contributor to the low flux of the Phillips lines. 
In the case of resonance fluorescence, as occurs for comets, 
the Phillips line is similarly weak unless the population in 
the $X^{1}\Sigma_{g}^{+}$ state is very much greater than in a $\Pi_{u}$ state. 
At low particle densities, as in the interstellar medium, the 
latter state is not populated; electric-quadrupole transitions 
drain population to the lowest levels of the $X$ state. This 
situation is, however, unlikely to prevail in V854 Cen. For 
R CrB, which may be taken as similar to V854 Cen, the sharp 
emission lines come from a region of high particle density 
(Rao et al. 1999) such that the a to $X$ populations must be 
close to their equilibrium value, i.e., sharp Phillips emission 
lines are almost certainly below our detection limit.

Rao et al. (1999) assembled a wealth of data on the 
E2 lines including $C_{2}$ Swan system lines seen throughout 
R CrB’s 1995-1996 decline to determine that the emitting
gas was warm and dense. The location of the gas relative to the star and the obscuring dust cloud could not be definitively established. Similarities between the atomic E2 lines of the two stars strongly suggest that V854 Cen’s E2 lines originate in the region providing its atomic E2 lines, and that this region resembles that around R CrB. Differences in physical condition and chemical composition may account for the fact that the Swan lines are more strongly in emission from V854 Cen.

Our temporal coverage of V854 Cen’s decline is limited but encourages the speculations that (i) the narrow C2 absorption lines appear only in decline, and (ii) the appearance of the E1 (transient) atomic lines and the C2 absorption lines may be related. The C2 Swan lines appear as weak photospheric absorption lines at maximum light. Their Phillips system counterparts are too weak to detect. The 1100K absorption lines are absent from our 1999 February spectrum. The E1 lines and Phillips absorption are both present in 1998 April but are seen neither in 1998 June when the star was fainter and E2 lines remained prominent. This suggests that the 1100K absorption is not merely related to the dust but more to the early stages of the decline. A possible connection is the presence of a shock, as considered by Woitke, Goeres & Sedlmayr (1996) and Woitke (1997) to be the trigger for a RCB decline. In their scenario, E1 lines originate in the hot gas immediately behind the shock and dust forms in cool dense gas further behind the outwardly moving shock front. Here, as for R CrB, the shock may propagate through the infalling gas betrayed by the red-shifted absorption lines of low excitation atomic lines.

In light of the detection of the Phillips absorption lines, we have reexamined spectra of R CrB obtained in its 1995-1996 decline (Rao et al. 1999). R CrB appears not to have shown these absorption lines in its decline (Figure 4) but did show the E1 high-excitation lines. This difference between V854 Cen and R CrB may reflect differences in physical conditions in the upper atmospheres or in chemical compositions. Such differences may also account for the far greater propensity of V854 Cen to go into decline. The high hydrogen to carbon ratio of V854 Cen has led Goeres (1996) to predict that formation of carbon-containing molecules and dust grains is controlled by acetylene (C2H2) rather than the C3 molecules that act as the throttle for ‘normal’ RCBs.

5 CONCLUDING REMARKS

For the first time, cold gas below the temperature required for soot formation has been detected around a RCB in its decline to a deep minimum. Our detection of absorption by cold C2 molecules around V854 Cen now needs to be followed by synoptic observations of this active RCB variable in order to trace the evolution of the cold gas and to place it relative to the star. Is the gas located behind a shock where, as some theories would suppose, dust formation is triggered? Or is it merely an innocent companion to the dust? We recognise that providing synoptic observations at an adequate spectral resolution and high temporal frequency is a substantial challenge. If the challenge can be met, the result will be a window into the time and place of dust formation, and, perhaps, prove the long-sought understanding of how the characteristic declines of RCBs are initiated.

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