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High-resolution spectroscopy of V854 Cen in decline – absorption and emission lines of C_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_2 Phillips system. The low rotational temperature, $T_{\rm rot} = 1150$ K, of the C_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 an RCB star.

Key words: stars: individual: V854 Cen – stars: variables: other.

1 INTRODUCTION

R Coronae Borealis stars are H-poor F–G type supergiants that decline in brightness unpredictably by up to 8 mag and remain below their normal brightness for periods of several weeks to months. It is generally accepted that these declines are caused by formation of a cloud of carbon soot that obscures the stellar photosphere. The unanswered questions, ‘what triggers cloud formation?’ and ‘where does the soot form?’ remain. 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 ($T \simeq 1100$ K) during the early decline of an 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 favourable 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, which confirmed that V854 Cen has a somewhat unusual composition among the RCBs for which abundance anomalies are a *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_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_2 molecule.

2 OBSERVATIONS

V854 Cen was observed on four occasions from the W. J. McDonald Observatory with the 2.7-m Harlan J. Smith reflector and the *2dcoudé* spectrograph (Tull et al. 1995). Details of the observations are given in Table 1. Fig. 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 $V \sim 10.3$, about 55 d after the onset of a decline that saw the star fade to $V \sim 13.6$ by 1998 late May. We re-observed the star on 1998 June 6 at $V \sim 11.7$ 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.

The cross-dispersed echelle spectra are at a resolving power of 60 000 with nominal coverage from 3800 to 10 200 Å. Echelle orders are incompletely captured on the CCD for wavelengths longward of 5500 Å. In addition, the southerly declination of the star (Dec. = −39°) and the northerly latitude of the observatory (Lat. = 31°) result in severe atmospheric dispersion and loss of

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Table 1. Spectroscopic observations of V854 Centauri.

Date	XJD[a]	V	S/N[b]	Phase[c]
1998 April 8	911.887	10.3	69	81.227
1998 April 10	913.832	10.3	53	81.272
1998 June 6	970.679	11.7	61	82.587
1999 Feb 10	1219.988	7.3	149	88.354

[a] XJD = JD − 245000.0.
[b] S/N ratio in continuum near 6560 Å.
[c] Pulsation phase from Lawson et al.'s (1999) ephemeris, where zero phase is light maximum.

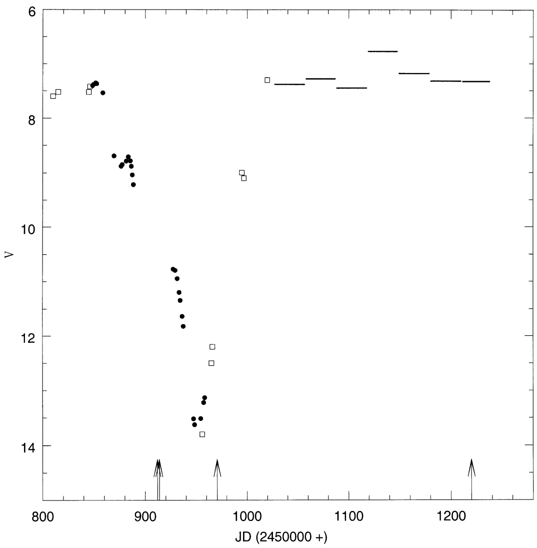

Figure 1. The light curve for V854 Cen from early 1998 to early 1999. Dots refer to V magnitudes from Lawson et al. (1999), open squares and dashes are visual estimates from the AAVSO. The Julian dates of our observations are indicated by arrows.

signal in the blue, such that the spectra are not useable for wavelengths shorter than about 4100 Å.

3 V854 CENTAURI IN DECLINE

Well-observed RCBs in decline – R CrB and RY Sgr – 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' lines (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-ionized metals (e.g., Ti II and Fe II) are prominent contributors of E1 and E2 lines. The E1 and E2 lines are sharp (FWHM $\sim 14\,\mathrm{km\,s^{-1}}$ in R CrB). In deep declines, a few broad emission lines are seen with FWHM $\sim 300\,\mathrm{km\,s^{-1}}$, with the Na D being the strongest.

In our spectra of V854 Cen, E1 lines, especially C I lines, are present in 1998 April: 46 C I lines from 6400 to 8800 Å give a velocity of $-16.7 \pm 2.8\,\mathrm{km\,s^{-1}}$. Emission had gone by 1998 June, with the same lines appearing in absorption at a velocity of $-24.0 \pm 2.4\,\mathrm{km\,s^{-1}}$, which is the (out-of-decline) mean velocity of $-25\,\mathrm{km\,s^{-1}}$ that is unchanged as the star undergoes small semiregular 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 8000 Å also appear to be affected by emission, i.e. the N I 8216 Å line has an equivalent width of 59 mÅ and a FWHM of 0.36 Å in April, but its normal values, as in the 1999 February spectrum, are 164 mÅ and 0.69 Å, 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 $-34 \pm 2\,\mathrm{km\,s^{-1}}$ in 1998 April. Some C I emission lines show P Cygni profiles with absorption also at $-34\,\mathrm{km\,s^{-1}}$. Emission from E1 and E2 lines affects almost all photospheric lines in 1998 April. With the decay of E1 lines, the photospheric velocity is measurable from the 1998 June spectrum: the result $-27 \pm 1\,\mathrm{km\,s^{-1}}$ is consistent with the systemic velocity. Lines of low and high excitation potential are at the systemic velocity in the 1999 February spectrum.

The E2 lines in the 1998 April and June spectra are slightly blueshifted with respect to the mean photospheric velocity. The peak velocity which is unchanged between April and June is $-30 \pm 1\,\mathrm{km\,s^{-1}}$, corresponding to a blueshift of about $5\,\mathrm{km\,s^{-1}}$, a typical value for the E2 lines of R CrB and RY Sgr. The degree of excitation appears to be similar to that of R CrB in its 1995–1996 decline, and the linewidths 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 Na D 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 mag fainter. Similarly, the broad lines of R CrB 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 redshifted relative to the systemic velocity: the mean velocity of $+15 \pm 2\,\mathrm{km\,s^{-1}}$ from 7 lines in the 1998 April spectra implies infall at $40\,\mathrm{km\,s^{-1}}$ relative to the photosphere. Similar redshifted lines were seen in R CrB. This redshifted absorption, which is also clearly seen in the red wing of prominent sharp (blueshifted) emission lines, is unlikely to be the residual of the photospheric line (assumed to be at the systemic velocity) because the redshifted absorption occurs outside the normal photospheric profile and many lines lack accompanying emission. The fact that the redshifted absorption appears in lines of different excitation potentials indicates that the responsible gas is warm. By 1998 June, the same lines were at $-13 \pm 2\,\mathrm{km\,s^{-1}}$, and they were at the systemic velocity (i.e. photospheric in origin) by 1999 February.

These snapshots of V854 Cen's spectrum suggest that 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 ($X\,^1\Sigma_g^+$, Ballik & Ramsay 1963; Huber & Herzberg 1979) and its upper state ($A\,^1\Pi_u$) has the excitation energy $T_e = 8391\,\mathrm{cm}^{-1}$. The Swan system's lower level is the lowest and very low-lying *triplet* state ($a\,^3\Pi_u$) with $T_e = 716\,\mathrm{cm}^{-1}$, and the upper state ($d\,^3\Pi_g$) is at $T_e = 20\,022\,\mathrm{cm}^{-1}$. 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 Fig. 2. The velocity, as measured from clean 0–0 lines, is $-27\,\mathrm{km\,s^{-1}}$, which is that of the E2 sharp emission atomic lines. The linewidth, 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 $T_{\mathrm{rot}} = 4625 \pm 300\,\mathrm{K}$ (see Fig. 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 vibrational temperature near 5000 K 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 in the 1998 April spectra but absent from the 1998 June spectrum. Fig. 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 a radial velocity of $-30.4 \pm 1.3\,\mathrm{km\,s^{-1}}$ from 15 lines, i.e. a small expansion velocity relative to the systemic velocity of

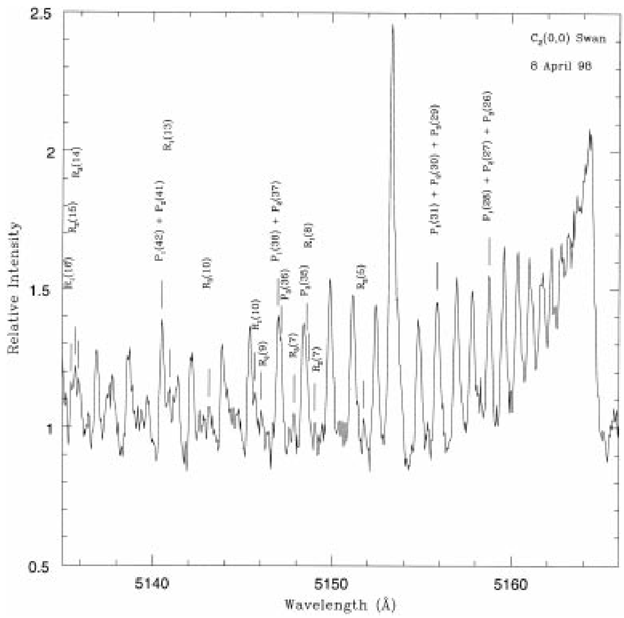

Figure 2. The C_2 Swan 0–0 P branch band-head on 1998 April 8. A few lines and blends are identified.

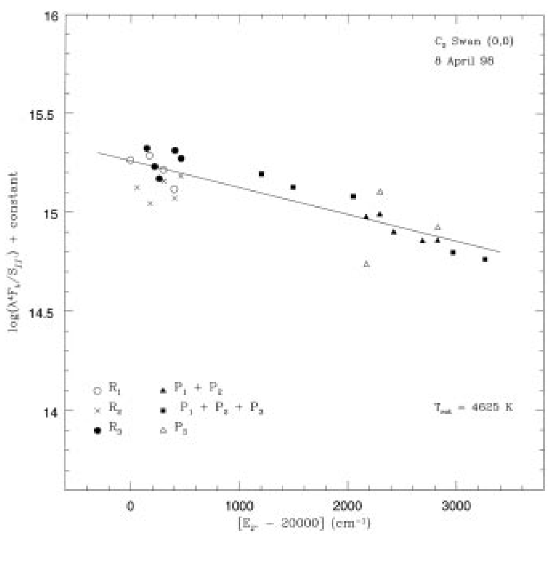

Figure 3. A standard Boltzmann plot compiled from Swan 0–0 lines and blends (see key on figure). The solid line is a least-squares fitted line corresponding to a rotational temperature of 4625 K.

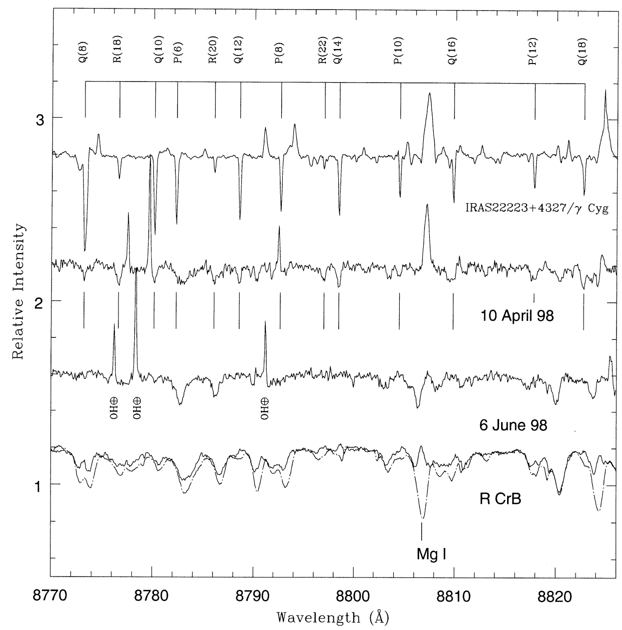

Figure 4. Spectra from 8770–8826 Å of V854 Cen and IRAS 2223+4327. Locations of C_2 Phillips 2–0 lines are indicated at the top of the figure and below the 1998 April 10 spectrum of V854 Cen. The Phillips lines are strongly present in IRAS 2223+4327 and the 1998 April spectra of V854 Cen but not in the 1998 June 6 spectrum. Two R CrB spectra are shown superimposed: the spectrum from 1995 September 30 (dash–dotted line) was taken at maximum light just prior to the 1995 decline; the spectrum from 1995 October 13 (solid line) was taken when the star was about 3 mag below maximum brightness, i.e. the star had faded by about the same amount as V854 Cen had on 1998 April 10.

$-25\,\mathrm{km\,s^{-1}}$. The velocity differs considerably from that ($+15\,\mathrm{km\,s^{-1}}$) of the redshifted 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 $T_{\mathrm{rot}} = 1150 \pm 70\,\mathrm{K}$ from levels $J'' = 4$ to 28 (see Fig. 5). We interpret this as a close approximation to the gas kinetic temperature. If, as occurs in interstellar diffuse clouds, the excitation of the C_2 molecule is greatly influenced by radiative pumping in the Phillips bands (and $X\,^1\Sigma_g^+ \rightleftharpoons \mathrm{a}\,^3\Pi_u$ radiative transitions), the Boltzmann plot is expected to be curved, with the 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 the diffuse clouds in ζ Oph give $T_{\mathrm{rot}} \simeq 40\,\mathrm{K}$ from the lowest levels and 785 K 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 $2 \times 10^{15}\,\mathrm{cm^{-2}}$.

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 $W_\lambda \propto f\lambda^2 NL$ where f and λ are the oscillator strength and wavelength of the line 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 favoured by a factor of about 7, with the greater f-value of the system 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 ($-30\,\mathrm{km\,s^{-1}}$ versus $-27\,\mathrm{km\,s^{-1}}$), 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 system line at about 0.2 times 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 $T_{\mathrm{rot}} = 4625\,\mathrm{K}$, it is readily shown that the flux in a Phillips 2–0 line is about 15 per cent that of the Swan 0–0 of a similar J value in the event in which reddening can 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 $\mathrm{a}\,^3\Pi_u$ 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 Swan 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 C_2 absorption lines appear only in decline, and (ii) the appearance of the E1 (transient) atomic lines and the C_2 absorption lines may be related. The C_2 Swan lines appear as weak photospheric absorption lines at maximum light. Their Phillips system counterparts are too weak to detect. The 1100-K absorption lines are absent from our 1999 February spectrum. The E1 lines and Phillips absorption are both present in 1998 April but neither of them is seen in 1998 June when the star was fainter and E2 lines remained prominent. This suggests that the 1100 K absorption is not merely related to the dust but also 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 an 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 redshifted absorption lines of low-excitation atomic lines.

In light of the detection of the Phillips absorption lines, we have re-examined 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 (Fig. 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 (C_2H_2), rather than the C_3 molecules that act as the throttle for 'normal' RCBs.

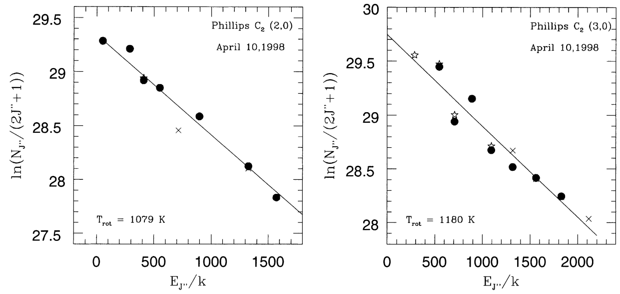

Figure 5. Standard Boltzmann plots for the C_2 Phillips absorption lines. Stars, dots and crosses refer to *P*, *Q* and *R* branch lines, respectively. The line is the least-squares fitted line corresponding to the rotational temperature indicated on the figure.

5 CONCLUDING REMARKS

For the first time, cold gas below the temperature required for soot formation has been detected around an RCB in its decline to a deep minimum. Our detection of absorption by cold C_2 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 recognize 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, provide the long-sought understanding of how the characteristic declines of RCBs are initiated.

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