

# The R Coronae Borealis stars: carbon abundances from forbidden carbon lines

Gajendra Pandey,<sup>1\*</sup> David L. Lambert,<sup>1</sup> N. Kameswara Rao,<sup>2</sup> Bengt Gustafsson,<sup>3</sup> Nils Ryde<sup>3</sup> and David Yong<sup>1</sup>

<sup>1</sup>*Department of Astronomy, University of Texas, Austin, TX 78712-1083, USA*

<sup>2</sup>*Indian Institute of Astrophysics, Bangalore 560034, India*

<sup>3</sup>*Astronomiska Observatoriet, Uppsala, Sweden S-751-20*

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## ABSTRACT

Spectra of several R Coronae Borealis (RCB) stars at maximum light have been examined for the [C I] 9850- and 8727-Å absorption lines. The 9850-Å line is variously blended with an Fe II and CN lines, but positive identifications of the [C I] line are made for R CrB and SU Tau. The 8727-Å line is detected in the spectrum of the five stars observed in this wavelength region. Carbon abundances are derived from the [C I] lines using the model atmospheres and atmospheric parameters used by Asplund et al.

Although the observed strength of a C I line is constant from cool to hot RCB stars, the strength is lower than predicted by an amount equivalent to a factor of 4 reduction of the  $gf$ -value of a line. Asplund et al. dubbed this ‘the carbon problem’ and discussed possible solutions.

The [C I] 9850-Å line seen clearly in R CrB and SU Tau confirms the magnitude of the carbon problem revealed by the C I lines. The [C I] 8727-Å line measured in five stars shows an enhanced carbon problem. The  $gf$ -value required to fit the observed [C I] 8727-Å line is a factor of 15 less than the well-determined theoretical  $gf$ -value. We suggest that the carbon problem for all lines may be alleviated to some extent by a chromospheric-like temperature rise in these stars. The rise far exceeds that predicted by our non-local thermodynamic equilibrium calculations, and requires a substantial deposition of mechanical energy.

**Key words:** stars: abundances – stars: atmospheres – stars: individual: R CrB – stars: individual: SU Tau – stars: variables: other.

## 1 INTRODUCTION

The rare class of R Coronae Borealis (RCB) variables continues to present fascinating puzzles. Two defining characteristics of these supergiants are the unpredictable fading of the star and the presence of helium, not hydrogen, as the most common constituent of the stellar atmosphere. The fadings are generally assumed to occur when a cloud of carbon soot forms on the line of sight to the star, but the formation process, and initial location and evolution of the cloud encompass unanswered questions. How a normal star or a pair of stars evolves to possess an H-deficient atmosphere has challenged theorists and observers alike. A leading idea is that an RCB star is the result of a merger of an He white dwarf with a C–O white dwarf. To develop observational tests of this and other ideas, one requires

accurate estimates of the elemental abundances for a representative sample of the RCB stars.

In attempting to supply these data, Asplund et al. (2000) uncovered yet another interesting puzzle which is discussed below. In RCB stars, as in normal stars, the strength of an absorption line is influenced by two principal factors: the ratio of the line to continuous opacity and the temperature gradient through the region of the atmosphere in which the line is formed. It has been suggested that photoionization of neutral carbon from high-lying levels appears to be the dominant source of continuous absorption across the visible spectrum (Searle 1961). A characteristic of RCB star spectra is a rich collection of absorption lines of neutral carbon from levels only slightly less excited than those contributing to the continuous opacity. Since the line and continuous opacity originate from similar excited levels of the neutral carbon atoms, their opacity ratio is quite insensitive to fundamental parameters of the stars such as effective temperature, surface gravity and the fractional carbon abundance

\*E-mail: pandey@iiap.res.in

**Table 1.** Table of observations; the stars are ordered by their effective temperatures decreasing from top to bottom.

Star	Date	$R =$ $\lambda/\Delta\lambda$	S/N at 8727 Å	S/N at 9850 Å	$V_{\text{rad}}$ km s <sup>-1</sup>
RCB stars:					
XX Cam	1997 October 9	60 000	...	185	11
XX Cam	1998 January 26	60 000	...	120	13
XX Cam	2002 November 17	60 000	...	186	11
XX Cam	2002 November 17	60 000	278	...	...
RY Sgr	1997 June 22	60 000	...	170	-30
RY Sgr	2002 July 31	120 000	300	200	-12
UV Cas	1996 July 24	60 000	...	140	-32
UV Cas	2002 November 15	60 000	...	120	-32
UV Cas	2002 November 15	60 000	178	...	...
VZ Sgr	1999 August 18	60 000	...	80	245
R CrB	1995 June 17	60 000	340	180	20
R CrB	1995 August 7	60 000	...	110	22
R CrB	1997 June 20	60 000	...	185	21
R CrB	2002 July 31	120 000	400	200	19
SU Tau	2002 November 15	60 000	...	100	43
SU Tau	2002 November 15	60 000	180	...	...
V482 Cyg	1996 July 24	60 000	...	90	-40
GU Sgr	1997 June 22	60 000	...	95	-45
Standard star:					
$\gamma$ Cyg	2002 July 31	120 000	520	230	...

(effectively, the C/He ratio once it exceeds 1 per cent – see also Schönberner 1975; Cottrell & Lambert 1982). For weak lines, this insensitivity extends to differences in the turbulent velocities.

This is observed in the RCB stars. A C I line retains its equivalent width even as ‘metal’ lines may vary considerably from star to star [see Fig. 1 in Rao & Lambert (1996)]. However, the predicted equivalent widths of the C I lines exceed the observed equivalent widths by a considerable factor. Expressed as the change in the *gf*-value of a line needed to bring the predicted in tune with the observed equivalent width, the disagreement amounts to a factor of 4. Asplund et al. (2000) dubbed this ‘the carbon problem’.

The principal purpose of this paper is to add a new clue to the solution of the carbon problem. That dimension is offered by the [C I] 8727- and 9850-Å lines and the estimate of the carbon abundance that they provide. We propose to investigate this aspect in more stars and to see whether a solution can be obtained for this puzzle. The present paper provides the results of these observations which, to our surprise, show an enhanced carbon problem.

## 2 OBSERVATIONS

High-resolution optical spectra of eight RCB stars (Table 1) were obtained at the W. J. McDonald Observatory 2.7-m telescope with the coude cross-dispersed echelle spectrograph (Tull et al. 1995). In addition,  $\gamma$  Cyg, a normal F-type supergiant, was also observed (Table 1) at  $R = 120\,000$ . The telluric absorption lines from the spectra of the programme stars were removed interactively using early-type rapidly rotating stars. We have used the Image Reduction and Analysis Facility (IRAF) software packages to reduce the spectra, and the task TELLURIC within IRAF to remove the telluric absorption lines.

The Th–Ar hollow cathode lamp fails to provide lines in the 9850-Å region for wavelength calibration. Plenty of Th–Ar lines are available shortward of 9670 Å to provide a wavelength solution to an accuracy of one-tenth of a pixel. We apply this solution for

the wavelengths longer than 9670 Å. To check the accuracy of the wavelength calibration in the 9850-Å region, the measured wavelengths of the atmospheric H<sub>2</sub>O lines are compared with those measured from the solar spectrum (Swensson et al. 1970). We measured the wavelengths of 11 atmospheric H<sub>2</sub>O lines finding agreement to  $0.003 \pm 0.02$  Å with those measured from the solar spectrum.

Sample portions of  $R = 120\,000$  and  $60\,000$  spectra are shown in Figs 1 and 2. Note that the spectra of the RCB stars are fully resolved at  $R = 60\,000$ . All spectra are aligned to the rest wavelengths of N I lines that fall in the wavelength regions. Stellar lines were identified using the revised Multiplet Table (Moore 1972), tables of spectra of H, C, N and O (Moore 1993), Kurucz’s list,<sup>1</sup> the Vienna Atomic Line Data base,<sup>2</sup> the new Fe I multiplet table (Nave et al. 1994), and a spectrum of  $\gamma$  Cyg, a normal F-type supergiant, as a reference.

All stars except V482 Cyg were observed at maximum light. Our spectrum of V482 Cyg was taken when the star was in a shallow minimum in 1996 July, about 2 mag below maximum light. It took the star about one year to return to maximum light.

## 3 LINE DATA AND IDENTIFICATIONS

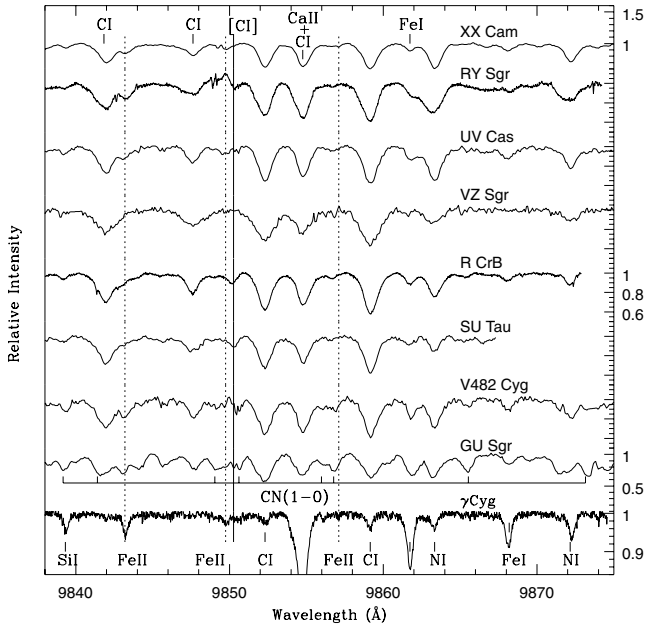
### 3.1 The [C I] lines

The standard reference for the C I spectrum (Moore 1993) gives a predicted wavelength of 8727.126 Å for the [C I]  $2p^2 \ ^1D_2 - 2p^2 \ ^1S_0$  transition and 9850.264 Å for the [C I]  $2p^2 \ ^3P_2 - 2p^2 \ ^1D_2$  transition. Wavelengths of the forbidden carbon lines have not been measured directly from laboratory sources.

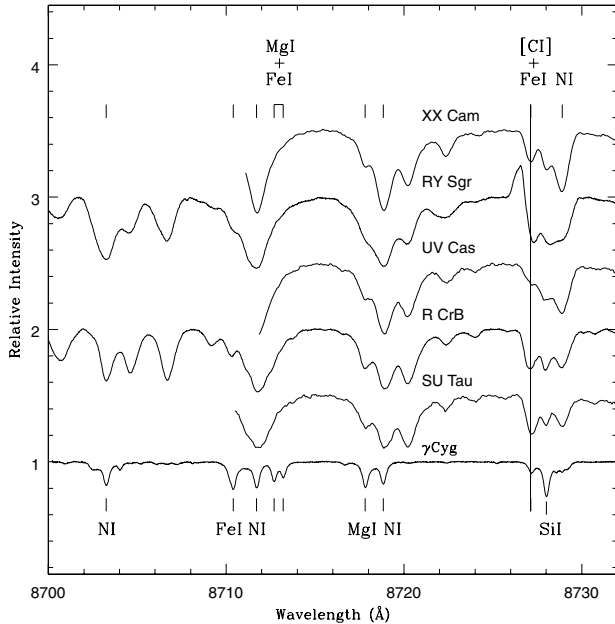
The predicted wavelength of the 8727-Å line is confirmed by the wavelength of the absorption line in the solar spectrum (Allende Prieto, Lambert & Asplund 2002) and the emission line in planetary nebulae (Liu et al. 1995). For the 8727-Å line, we adopt

<sup>1</sup> <http://kurucz.harvard.edu>

<sup>2</sup> <http://www.astro.univie.ac.at/~vald>



**Figure 1.** The spectra of the RCB stars in the region of the [C I] 9850.264-Å line, which is indicated by a vertical solid line, are plotted with their effective temperatures increasing from bottom to top. The spectrum of  $\gamma$  Cyg is also plotted. The positions of a number of other atomic and some CN lines are also marked, and the vertical dotted lines indicate the Fe II features. The relative intensity scale for GU Sgr and XX Cam is different from that for the other RCB stars.



**Figure 2.** The spectra of RCB stars in the region of the [C I] 8727.126-Å line, which is indicated by a vertical solid line, are plotted with their effective temperatures increasing from bottom to top. The spectrum of  $\gamma$  Cyg is also plotted. The positions of the key lines are also marked.

$\log gf = -8.14$  (Galavis, Mendoza & Zeppen 1997). The lower excitation potential is 1.264 eV. There is a blending Fe I line for which we adopt  $\log gf = -4.4$  (Allende Prieto et al. 2002), but this line is not a significant contributor to the spectrum of an RCB star.

For the 9850-Å line, we adopt the predicted wavelength. There is supporting evidence from our spectra for this wavelength. The 2002 July spectra of RY Sgr show the 9850- and 8727-Å [C I] lines in emission (see Figs 1 and 2). Adopting 8727.126 Å as the rest wavelength for the latter emission and assuming that the two lines have the same velocity, we find that the astrophysical wavelength of the 9850-Å emission is close to the predicted wavelength. Liu et al. (1995) report, however, a rest wavelength of  $9850.36 \pm 0.01$  Å from detections of the line in four planetary nebulae. The 0.1 Å or 3 km  $s^{-1}$  difference between the wavelength predicted from energy levels and that observed from planetary nebulae does not seriously impact derivation of the carbon abundance from the line in the RCB star spectra. The transition probability for the 9850-Å line is taken from Galavis et al. (1997) who give  $A = 2.23 \times 10^{-4} s^{-1}$  or  $\log gf = -10.79$  with an uncertainty of about 0.04 dex. The lower excitation potential is a mere 0.005 eV.

Two additional lines complete multiplet 1F. The stronger line with a  $gf$ -value about 3 times smaller than for the 9850-Å line is at  $9824.30 \pm 0.05$  Å (Liu et al. 1995) and irretrievably blended in the spectra of cooler RCB stars (GU Sgr, V482 Cyg, SU Tau and R CrB). In the spectra of VZ Sgr, UV Cas and XX Cam, the 9824.30-Å line is absent, but this is as expected from the signal-to-noise ratio and the estimated strength of the observed 9850-Å line. The third [C I] line at 9808.3 Å is expected to be 4000 times weaker than the 9850-Å line, and undetectable. (The multiplet  $2F 2p^2 \ ^3P_1 - 2p^2 \ ^1S_0$  transition at 4621.57 Å with  $\log gf = -11.12$  is almost certainly blended, as the blue spectral region of an RCB star is rich in strong lines.)

### 3.2 Overview of the spectra

The region around 9850 Å is shown in Fig. 1, where the stars are ordered by increasing temperature from bottom to top. The spectrum of the normal yellow supergiant  $\gamma$  Cyg is shown at the bottom. In the spectra of the hottest stars, the strongest lines are from C I and Ni transitions with weaker lines of Si I, Fe I and Fe II. The [C I] line falls in the red wing of an Fe II line. Spectra of the coolest stars GU Sgr and V482 Cyg show additional lines which we identify as high rotational lines of the 1-0 band of the CN molecule's red system (Davis & Phillips 1963). These CN lines are prominent in the spectra of GU Sgr and V482 Cyg and traceable in SU Tau, R CrB and RY Sgr. Two CN lines bracket the [C I] line.

Inspection of Fig. 1 shows several additional features of interest. As anticipated, the strength of a given C I line is unchanged along the temperature sequence from XX Cam at the high-temperature end to GU Sgr at the low-temperature end. Also anticipated is the very large width of all absorption lines in the spectra of RCB stars. Compare the widths with those of lines in  $\gamma$  Cyg, which itself is commonly referred to as showing broad lines. A surprise is the appearance of emission in the RY Sgr spectrum near the wavelength of the [C I] line. The illustrated spectrum is from 2002 July 31 in which the 8727-Å line is also in emission. A spectrum from 1997 June 22 also shows emission but to the red of the wavelength of the [C I] line. The possibility of emission contaminating the absorption line is an unfortunate complication.

The [C I] 8727-Å line (Fig. 2) is slightly blended with a Si I line. Emission is very pronounced in the spectrum of RY Sgr. The central line depths of the [C I] line run from about 16 per cent for SU Tau to 36 per cent for RY Sgr with no obvious systematic trend with the effective temperature.

#### 4 SPECTRAL SYNTHESIS: PROCEDURE

The fact that the [C I] lines are blended with other lines requires that the carbon abundance be extracted by spectral synthesis. In addition to synthesizing the [C I] line and its blends, we use lines of C I, N I, Si I, Fe I and Fe II to obtain abundances and compare with values given by Asplund et al. (2000).

Synthetic spectra were generated using the H-deficient model atmospheres computed by Asplund et al. (1997) and the Uppsala spectral synthesis code `BSYNRUN`. Models corresponding to a C/He ratio of 1 per cent by number were chosen. This composition is equivalent to a carbon abundance  $\log \epsilon(\text{C}) = 9.54$  on the scale  $\sum \mu_i \epsilon_i = 12.15$ , where  $\mu_i$  is the mean atomic weight of element  $i$ . Stellar parameters derived by Asplund et al. (2000) were adopted as our initial values. Synthetic spectra were convolved with a Gaussian profile to account for the combined broadening of stellar lines by the atmospheric macroturbulent velocity, rotational broadening, and the instrumental profile.

##### 4.1 The 9850-Å region

The 9850-Å [C I] line may be blended with Fe II and CN lines. The Fe II line at 9849.74 Å has a lower excitation potential of 6.729 eV. To obtain the  $gf$ -value of the line, we use the spectrum of  $\gamma$  Cyg where the Fe II line is present. With a model atmosphere constructed for the stellar parameters and iron abundance given by Luck & Lambert (1981), we find  $\log gf = -2.60$ . The basic data for the CN 1–0 lines were taken from Kurucz's line list and checked against the SCAN tape (Jørgensen & Larsson 1990) and a recipe given by Bakker & Lambert (1998). A dissociation energy of 7.65 eV was adopted for the molecule (Bauschlicher, Langhoff & Taylor 1988). Unblended CN lines away from the 9850-Å feature were fitted by adjusting the N abundance, and this abundance used in computing the CN lines blended with the [C I] line. An estimate of the N abundance was obtained not only from the CN lines but also from N I lines near the [C I] lines. The  $gf$ -values for the N I lines were taken from the compilation of Wiese, Fuhr & Deters (1996).

The C I lines at 9852.27 Å, a blend of two lines, and 9859.15 Å (Fig. 1) have also been used for estimating the C abundance. Their  $gf$ -values are determined by inversion of their equivalent widths in the  $\gamma$  Cyg spectrum using the C abundance derived from a set of weak C I lines at shorter wavelengths.

##### 4.2 The 8727-Å region

The red wing of the [C I] line is blended with a Si I line (Fig. 2). The  $gf$ -value of the latter line is derived from its equivalent width in the solar spectrum. The  $gf$ -value of the N I line to the red of the Si I line is taken from Wiese et al. (1996). Spectral synthesis of this region was confined to a 6-Å window around the [C I] line.

#### 5 SPECTRAL SYNTHESIS: RESULTS

The [C I] lines were sought in order to shed new light on the 'carbon problem'. Asplund et al. (2000) suggested that the 9850-Å [C I] line was not subject to the carbon problem. Their analysis was flawed in that the contributions of the blending Fe II and CN line were not considered.

In addition to fitting the [C I] lines, we analysed other lines in order to check the abundances given by Asplund et al. (2000). To within the uncertainties of the analyses and with the exception of

V482 Cyg (see below), we confirm the result for carbon using C I lines in the 9850-Å region, the N abundance using N I lines in the 9850- and 8727-Å regions, the Si abundance from Si I lines in the 9850- and 8727-Å regions, and the Fe abundance from Fe I and Fe II lines in the 9850-Å region. The CN 1–0 lines were also used to check the N abundance. In these atmospheres, molecules are trace species the formation of which does not affect the partial pressures of the constituent atoms. Then, consideration of the ratio of line to continuous opacity shows that the strength of a CN line should be dependent on the N abundance but independent of the C abundance.

Following remarks about  $\gamma$  Cyg, we discuss the RCB stars in order of decreasing effective temperature. It should be noted that the C abundances given here for the RCB stars are not self-consistent – the model atmospheres and their continuous absorption were calculated assuming a logarithmic C abundance of 9.54. If the same abundance is adopted for the calculations of the carbon lines – permitted and forbidden – the predicted and observed equivalent widths are in disagreement. Thus the C abundance derived here for the RCB stars is basically a measure of the inconsistency, which we term the carbon problem.

##### 5.1 $\gamma$ Cyg

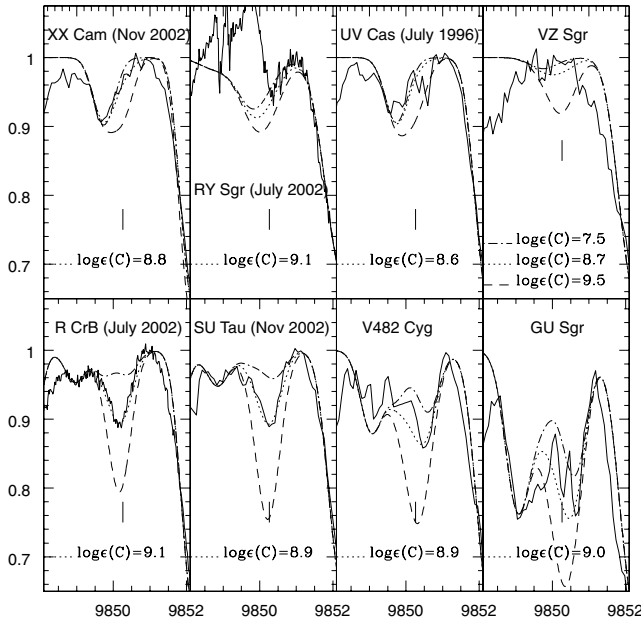
Our analysis of permitted and forbidden C I lines uses a MARCS model atmosphere (Gustafsson et al. 1975) for the atmospheric parameters derived by Luck & Lambert (1981). The 8727-Å [C I] line (Fig. 2) yields the abundance  $\log \epsilon(\text{C}) = 7.88$ . The 9850-Å [C I] line is not detectable and the upper limit to its equivalent width corresponds to  $\log \epsilon(\text{C}) \leq 8.18$ . A selection of 14 C I lines from 5380 to 8873 Å with  $gf$ -values from Wiese et al. (1996) give the abundance  $\log \epsilon(\text{C}) = 7.94 \pm 0.14$ . These lines range in equivalent width from 6 to 82 mÅ. For  $\gamma$  Cyg, it is seen that the C I lines and the 8727-Å forbidden line return the same abundance within the uncertainties. This result is in sharp contrast to the results from the RCB stars.

##### 5.2 XX Cam

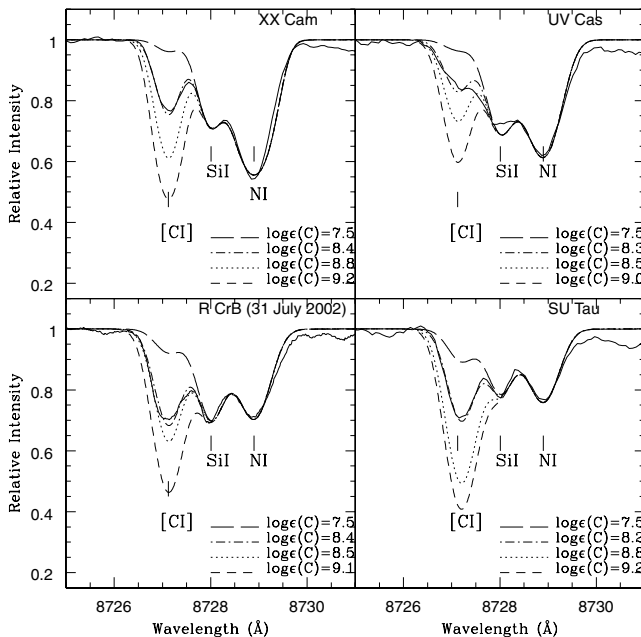
The 9850-Å feature is dominated by the Fe II line such that we can set only an upper limit to the [C I] contribution and the associated C abundance of  $\log \epsilon(\text{C}) \leq 8.8$  (Fig. 3). The 8727-Å line (Fig. 4) is fitted with an abundance  $\log \epsilon(\text{C}) = 8.4$ . The limit from the 9850-Å line to the C abundance is consistent with that from the 8727-Å line. The two C I lines near 9850 Å give an abundance consistent with the C abundance of  $\log \epsilon(\text{C}) = 9.0 \pm 0.4$  from Asplund et al., who used a collection of C I lines and Opacity Project  $gf$ -values (Luo & Pradhan 1989; Hibbert et al. 1993; Seaton et al. 1994).

Asplund et al. put the uncertainty in  $T_{\text{eff}}$  at about  $\pm 250$  K which corresponds to corrections to abundances derived from C I and [C I] lines of 0.05 and 0.2 dex, respectively. The uncertainty in  $\log g \simeq \pm 0.5$  provides only minor corrections to the abundances. An additional potential source of uncertainty is the adopted microturbulent velocity of  $\xi = 9.0 \text{ km s}^{-1}$  (Asplund et al. 2000). A change of  $\xi$  by  $\pm 2 \text{ km s}^{-1}$  changes the C abundance by 0.2 dex from the C I lines and by only 0.05 dex from the [C I] 8727-Å line. These estimates of uncertainty do not allow the 0.6-dex difference in the C I and [C I] abundances.

The carbon problem for the [C I] line is even more severe as seen for the 8727-Å [C I] line which gives an abundance 0.6 less than the C I lines and 1.1 dex less than the input abundance.



**Figure 3.** Observed (solid line) and synthetic [C I] 9850.264-Å line profiles of RCB stars. Synthetic profiles, including the blends, are shown for each star for three different abundances. The maximum abundance of  $\log \epsilon(C) = 9.5$ , the model input abundance, is shown by the long dashes and in no case does this fit the observed feature. The minimum abundance of  $\log \epsilon(C) = 7.5$  shows in effect the predicted spectrum for no contribution from the [C I] line (see dot-dashed line). The best-fitting synthetic spectrum is shown by the dotted line and the corresponding abundance is indicated in each panel.



**Figure 4.** Observed [C I] 8727.126-Å line profiles (solid lines) of RCB stars. Synthetic spectra are shown for four C abundances, as shown in the figure.

### 5.3 RY Sgr

The 2002 July 31 spectrum shows emission in the blue wing of the 8727-Å forbidden line. Peak emission occurs at a velocity of  $-29 \text{ km s}^{-1}$ . This is blueshifted by about  $17 \text{ km s}^{-1}$  from the photospheric

velocity of  $-12 \text{ km s}^{-1}$ . The emission line has a width (FWHM) of about  $19 \text{ km s}^{-1}$ . A spectrum taken on the same night shows emission at  $9850 \text{ Å}$  (Fig. 1). Emission at [C I] may be a common occurrence for this star. Our 1997 June 22 spectrum shows  $9850 \text{ Å}$  in emission at the radial velocity of  $-10.5 \text{ km s}^{-1}$  equivalent to a redshift of  $19.5 \text{ km s}^{-1}$  relative to the photosphere. This spectrum does not include the region around the 8727-Å line.

RY Sgr exhibits a pulsation with an amplitude of about  $35 \text{ km s}^{-1}$  (Lawson, Cottrell & Clark 1991). The mean or systemic velocity was given as  $-21 \text{ km s}^{-1}$  by Lawson et al. (1991). Relative to this velocity the emission at  $8727 \text{ Å}$  in the 2002 spectrum is blueshifted by about  $8 \text{ km s}^{-1}$ . Perhaps, the emission at maximum light is related to the fact that RY Sgr is a large-amplitude radial velocity pulsator. There is no hint of emission in our spectra of the other RCB stars, even in V482 Cyg observed below maximum light.

By inspection, the  $9850\text{-Å}$  blend of Fe II and [C I] lines is very similar to that of XX Cam, and hence the forbidden line is a minor contributor to the absorption feature. Synthesis of the 8727-Å line suggests that emission overlies the absorption line, and one might suppose that an abundance  $\log \epsilon(C) \sim 9.2$  is a lower limit, but this assumes that the emission comes from a region exterior to the regions in which the absorption line is formed. This is not necessarily a valid assumption for RY Sgr with its large pulsation and evidence for an internal shock. We decline to quote a carbon abundance, but a clue might be derived from RY Sgr observations that the emission affects both [C I] lines. The estimations from the red absorption wing (assumed to be unaffected by emissions) of both these [C I] lines suggest the same carbon abundance of about 9.2 which agrees with that from C I lines.

With the adopted model, the CN lines return a N abundance about 0.6 dex higher than from the N I lines used here and by Asplund et al. This difference between N abundances can be eliminated by lowering the adopted  $T_{\text{eff}}$  by about 200 K, or by a combination of a smaller  $T_{\text{eff}}$  change accompanied by a reduction of  $\log g$ . These adjustments are within the uncertainty limits considered reasonable by Asplund et al.

### 5.4 UV Cas

The 8727 Å line is reasonably well fitted with the abundance  $\log \epsilon(C) = 8.3$  (Fig. 4). Two observations show no convincing evidence for the  $9850\text{-Å}$  [C I] line, indicating  $\log \epsilon(C) \leq 8.7$  (Fig. 3). The two C I lines in the  $9850\text{-Å}$  region suggest an abundance close to  $\log \epsilon = 9.0$ , a value only 0.2 dex less than that obtained by Asplund et al. (2000). The CN lines are not detectable in our spectra. UV Cas joins XX Cam in showing a larger carbon problem for the 8727-Å line than for the C I lines.

### 5.5 VZ Sgr

This RCB star was classified as a ‘minority’ star by Lambert & Rao (1994), i.e. the metal lines are weak. This is evident from Fig. 1 which shows that the Fe I and Fe II lines are absent from the spectrum of VZ Sgr. Unfortunately, the region around  $8727 \text{ Å}$  has not yet been observed. Synthesis (Fig. 3) suggests an upper limit  $\log \epsilon(C) \leq 8.7$  for the [C I]  $9850\text{-Å}$  line, a limit clearly below the input abundance of 9.5. The two C I lines give  $\log \epsilon(C) = 9.1$ . Asplund et al. gave  $\log \epsilon(C) = 8.8 \pm 0.3$ .

### 5.6 R CrB

At  $8727 \text{ Å}$  the synthesis corresponding to  $\log \epsilon(C) \simeq 8.4$  provides a fair fit to the observed high-resolution profile of 2002 July 31

(Fig. 4). A lower resolution ( $R = 60\,000$ ) spectrum of 1995 June 17 provides the same abundance. In neither spectrum is there a hint that emission has distorted the absorption profile.

The 9850-Å syntheses include the CN lines blending with the [C I] and Fe II feature. In the high-resolution spectrum of 2002 July 31, the CN 1–0 lines are blueshifted by  $3.6\text{ km s}^{-1}$  relative to the high-excitation lines of C I and N I. Since the [C I] line and CN lines are all of low excitation, we assume that they have a common blueshift. Synthetic spectra (Fig. 3) indicate an abundance  $\log \epsilon(\text{C}) = 9.1$ . Examination of our library of 9850-Å spectra of R CrB (e.g. Rao & Lambert 1997; Rao et al. 1999) shows that the velocity shift between CN and the C I and N I varies during the pulsation of the star, and this shift ranges from  $-3.0$  to  $+4.0\text{ km s}^{-1}$ . Syntheses taking into account the velocity shift return the same abundance from four different spectra. If the blueshift is neglected, the fit to the 9850-Å feature is less satisfactory but the derived carbon abundance is little affected. Asplund et al.’s atmospheric parameters are used in all cases. The C I lines near 9850 Å are well fitted with a similar abundance [ $\log \epsilon(\text{C}) = 9.2$ ], an abundance equal to that determined by Asplund et al.

The 9850-Å line confirms the abundance obtained from C I lines, but the 8727-Å line gives an abundance 0.7 dex below that from the 9850-Å line or 1.1 dex below the input carbon abundance of the model.

The N I lines in the 8727- and 9850-Å regions give the abundance  $\log \epsilon(\text{N}) = 8.2$ , a value consistent with the result of  $8.4 \pm 0.2$  given by Asplund et al. The observed CN 1–0 lines are well matched with the abundance  $\log \epsilon(\text{N}) = 8.2$ . This may be fortuitous agreement because the sensitivity of the CN line strengths to a change of the atmospheric parameters, especially to  $T_{\text{eff}}$ , is high. Note that a change of 250 K changes the required abundance by 0.5 dex.

### 5.7 SU Tau

The abundance  $\log \epsilon(\text{C}) = 8.2$  provides an excellent fit to the observed [C I] line at 8727 Å (Fig. 4), whereas  $\log \epsilon(\text{C}) = 8.9$  is required for an equivalent fit to the observed 9850-Å feature (Fig. 3). For this fit, the CN lines are blueshifted by  $6\text{ km s}^{-1}$  from the high-excitation atomic lines. This shift is assumed to apply to the [C I] line also, but the derived abundance is not critically influenced by the shift. The abundance from the 9850-Å [C I] line is consistent with that derived by us from the 9850-Å region’s C I lines and the C I lines used by Asplund et al. In contrast and consistent with the results for XX Cam and R CrB, the 8727-Å line gives a markedly lower carbon abundance.

The N abundance reported by Asplund et al. was based on just two N I lines. Examination of our superior spectra provides a more accurate equivalent width for one line. The other line is not present in our spectrum. We identify a third line. We adopt Wiese et al. (1996)’s  $gf$ -value and derive the N abundance  $\log \epsilon(\text{N}) = 7.9$ . We suggest that this is a more reliable estimate than Asplund et al.’s value of 8.5. The N abundance estimate from the CN lines is 0.5 dex lower. The difference is erasable with minor adjustments to the adopted atmospheric parameters, such as an increase of  $T_{\text{eff}}$  by only 140 K.

### 5.8 V482 Cyg

There is a hint of emission at the 9850-Å [C I] line. Examination of the three individual exposures shows that this ‘emission’ occurs in only one exposure, that being the one with the lowest signal-to-noise ratio. We, therefore, consider the emission to be an artefact

which is removed in Fig. 3. A fit to the absorption feature suggests an abundance upper limit  $\log \epsilon(\text{C}) \leq 8.9$ .

In conflict with this upper limit, the C abundance of  $\log \epsilon(\text{C}) = 9.5 \pm 0.3$  is derived from C I lines in our spectrum. Asplund et al. obtained  $\log \epsilon(\text{C}) = 8.9$  from C I lines. Examination of our spectrum shows that C I lines across the spectrum are systematically stronger than reported by Asplund et al. This strengthening and the adoption of the same model as Asplund et al. necessarily result in a higher carbon abundance. Recall that the star was 2 mag below maximum light. We suppose that the atmospheric structure differed from that prevailing at maximum light. The temperature gradient may have been steeper in decline than at maximum light. A very similar strengthening of C I (and other) lines was noted by Rao et al. (1999) in spectra of R CrB taken early in a deep decline.

The N I lines give an abundance 0.8 dex higher than that from the CN lines. Erasure of the N I–CN discrepancy requires a different choice of atmospheric parameters. The possibilities range from raising  $T_{\text{eff}}$  by 400 K at the adopted  $\log g$  to lowering  $\log g$  by about 0.8 dex at the adopted  $T_{\text{eff}}$ . These are not unacceptable changes given that the atmosphere may have been perturbed.

### 5.9 GU Sgr

The blend containing the 9850-Å [C I] line is contaminated with CN lines which are strong in this spectrum. Our syntheses suggest an upper limit  $\log \epsilon(\text{C}) \leq 9.0$ , a value consistent with Asplund et al.’s value of 8.8.

Analysis of the CN lines gives a N abundance of  $\log \epsilon(\text{N}) = 8.1$ . Since the N I lines in the 9850-Å region are blended, we compare the CN-based abundance with the result  $\log \epsilon(\text{N}) = 8.7 \pm 0.5$  given by Asplund et al. The difference may be removed by a modest (250 K) increase of the adopted  $T_{\text{eff}}$  at the adopted  $\log g$ .

### 5.10 Summary of the carbon abundances

Our analyses use the appropriate MARCS model for the atmospheric parameters recommended by Asplund et al. and C/He = 1 per cent by number. This input abundance corresponds to a carbon abundance  $\log \epsilon(\text{C}) = 9.5$ . In Table 2, we summarize the carbon abundances derived from the two [C I] lines, and the C I-based abundance given by Asplund et al. illustrating the carbon problem.

**Table 2.** Photospheric C abundances from C I and [C I] lines.

Star	$T_{\text{eff}}$ K	Model <sup>a</sup>		$\log \epsilon(\text{C})$			
		$\log g$ cm s <sup>-2</sup>	$\xi$ km s <sup>-1</sup>	C I <sup>a</sup>	C I <sup>b</sup>	[C I] 9850 Å	[C I] 8727 Å
RCB stars:							
XX Cam	7250	0.75	9.0	9.0	8.9	<8.8	8.4
RY Sgr	7250	0.75	6.0	8.9	9.3	...	...
UV Cas	7250	0.50	7.0	9.2	9.0	<8.7	8.3
VZ Sgr	7000	0.50	8.0	9.1	9.1	<8.7	...
R CrB	6750	0.50	7.0	9.2	9.2	9.1	8.4
SU Tau	6500	0.50	7.0	8.8	9.0	8.9	8.2
V482 Cyg	6500	0.50	4.0	8.9	9.6	<8.9	...
GU Sgr	6250	0.50	7.0	8.8	9.3	<9.0	...
Standard star:							
$\gamma$ Cyg <sup>c</sup>	6100	0.55	3.5	7.9	...	<8.2	7.9

<sup>a</sup>Asplund et al. (2000) for R CrB stars; the expected C abundance is 9.54 when C/He of 1 per cent models are used; Luck & Lambert (1981) for  $\gamma$  Cyg. <sup>b</sup>Based on two C I lines near 9850 Å. <sup>c</sup>See Section 5.1 of the text.

Except for V482 Cyg, the carbon abundance derived from the two 9850-Å region C I lines is in good agreement with that obtained by Asplund et al.

Table 2 shows that a carbon problem extends to the 9850-Å forbidden line. This conclusion is contrary to that reached by Asplund et al. from analysis of equivalent widths of the 9850-Å line. The explanation is that Asplund et al. did not recognize that the [C I] line was a blend. In the case of V482 Cyg, which was observed 2 mag below maximum light, the carbon problem has vanished for the C I lines but not for the 9850-Å [C I] line. This is the only case where the C I lines and 9850 Å differ in the abundance that they provide.

Surprisingly, the 8727-Å [C I] line offers further information on the carbon problem. For each of the four stars for which we have observed the 8727-Å line, the derived abundance is less than that from the C I lines. In the case of R CrB and SU Tau, the 8727-Å line gives an abundance 0.7 dex less than that derived from the 9850-Å line. That the two forbidden lines give very different abundances is especially puzzling if these lines are formed, as expected, in or close to local thermodynamic equilibrium (LTE) and, as might be supposed, are a product of the stellar photosphere, i.e. a region with the temperature decreasing monotonically outward. An unidentified atomic line superimposed on the 8727-Å forbidden line would mean that we have overestimated the carbon abundance from that line. In this scenario, the carbon problem is more severe for both of the [C I] lines than for the C I lines. However, it is difficult to find a carrier for a line that is strong in R CrB and SU Tau but weak in other RCB stars and  $\gamma$  Cyg.

The sensitivities of the permitted and forbidden lines to the choice of model atmosphere are different. To illustrate these sensitivities, we give in Table 3 the abundances derived from the lines of R CrB for a series of model atmospheres centred on Asplund et al.'s choice of  $(T_{\text{eff}}, \log g, \xi) = (6750, 0.5, 7)$ . The carbon abundance from C I lines is, as expected from the insensitivity of the ratio of line to continuous opacity to physical conditions, almost independent of the choice of model. The abundance is also insensitive to the choice of the microturbulent velocity  $\xi$  for a weak line but not for a strong line. In Table 3, the mean C abundance derived from weak and strong permitted lines is given. The abundance from the forbidden lines is insensitive to the choice of the surface gravity but dependent on  $T_{\text{eff}}$ . We note that the change of  $\pm 250$  K in  $T_{\text{eff}}$  leads to a change in the carbon abundance of  $\pm 0.2$  dex. There is no dependence on  $\xi$ . The  $T_{\text{eff}}$  and  $\log g$  sensitivities are not very different for the hottest stars (XX Cam and RY Sgr) and the coolest (GU Sgr).

To increase the carbon abundance from the 9850-Å [C I] line to the input abundance [ $\log \epsilon(\text{C}) = 9.5$ ] requires that the  $T_{\text{eff}}$  of R CrB and SU Tau be raised about 500 and 750 K, respectively. These increases not only are outside the bounds considered acceptable by Asplund et al., but also do not remove the carbon problem for the permitted carbon lines. In addition, they introduce a discrepancy

between the N abundances from the N I and CN lines. Also note that the higher temperatures do not eliminate the abundance difference of 0.7 dex from the 9850- and 8727-Å forbidden lines of R CrB and SU Tau. In short, the [C I] lines are part of a now enlarged carbon problem.

## 6 DISCUSSION

Possible solutions to the carbon problem presented by the C I lines were discussed by Asplund et al. (2000 – see also Gustafsson & Asplund 1996). Two proposed solutions were suggested by Asplund et al. as worthy of further consideration: the  $gf$ -values of the C I lines are in error, or theoretical model atmospheres are a misrepresentation of the temperature structure of real RCB stars. In addition to commenting on these solutions as they affect the forbidden lines, we examine departures from LTE as they affect line formation. Finally, we discuss hand-crafted model atmospheres including models with a chromosphere (a temperature rise in the outer layers).

### 6.1 The $gf$ -values

The  $gf$ -values of the [C I] lines are known accurately from theoretical calculations. Confirmation and extension of the carbon problem from the forbidden lines strongly suggest that the  $gf$ -values of the permitted lines cannot be primarily responsible for the problem.

### 6.2 Non-LTE effects

Non-LTE effects in neutral carbon atoms in RCB star atmospheres were evaluated by Asplund & Ryde (1996). Their results indicate that departures from LTE are confined to low optical depths. Effects on the C I lines are slight because a line and the continuum are formed deep in the atmosphere between levels in the carbon atom with small and very similar departures from LTE. Gustafsson & Asplund (1996) give the correction to the LTE abundance from C I lines as less than 0.1 dex and suggest that  $+0.02$  dex is a typical value. Thus non-LTE effects cannot account for the 0.6 dex typical carbon problem arising from the permitted lines. Departure coefficients given by Asplund & Ryde (1996) show that a non-LTE correction to the LTE abundance from a forbidden line is also very small and cannot be the source of the carbon problem of the line. These non-LTE calculations adopt a model computed in LTE.

Carbon problems may be reduced or even eliminated by invoking a chromosphere. A temperature rise at the top of the photosphere is possible even in the absence of mechanical energy deposition. This non-LTE effect, sometimes called the Cayrel mechanism (Cayrel 1963), is discussed by Mihalas (1978). To assess the temperature rise for a RCB star due to the Cayrel mechanism, non-LTE effects on the populations of the carbon atom were included in the computation of the model atmosphere. These non-LTE effects on the carbon level populations were calculated using MULTI (Carlsson 1986), with the modelled carbon atom described in Asplund & Ryde (1996). Realistic background fluxes, computed with the MARCS model atmosphere code, were included. Typical departure coefficients [ $b = n/n(\text{LTE})$ , where  $n$  is the occupation number density] of about  $b = 1$  for the lower C I levels,  $b = 1.4$  for intermediate ones and  $b = 0.6$  for the upper ones were obtained. These figures were found to be characteristic of the depth interval  $-4 < \log \tau_{\text{Ross}} < -3$ , (where  $\tau_{\text{Ross}}$  is the Rosseland mean optical depth) with much smaller and opposite effects at larger optical depths. These departures from LTE should mainly affect the opacities. C I is also an important electron contributor, but our calculations show only an underionization of less than 10 per cent at small depths.

**Table 3.** Carbon abundances for R CrB for various model atmospheres.

Model $T_{\text{eff}}, \log g, \xi$	C I	$\log \epsilon(\text{C})$	
		[C I] 9850 Å	[C I] 8727 Å
6750, 0.5, 7	9.2	9.1	8.4
6500, 0.5, 7	9.2	8.9	8.2
7000, 0.5, 7	9.3	9.3	8.6
6750, 0.0, 7	9.3	9.1	8.4
6750, 1.0, 7	9.1	9.1	8.4
6750, 1.0, 9	8.9	9.1	8.4
6750, 1.0, 5	9.3	9.1	8.4

We then brought these results into the MARCS program in order to include their effect on the continuous opacities. This procedure is not fully self-consistent – the models are still LTE models – but the main effects of the departures on the opacities are modelled in a reasonable way. They essentially diminish the C I opacities longwards of 6000 Å, to 0.6 times the LTE value, and increase them shortwards of that wavelength to 1.4 times the LTE value. This was applied for the uppermost atmosphere with a decrease corresponding to our non-LTE results at greater depth. A Cayrel effect resulted, as expected, with a heating of the upper layers, but only by about 1–6 K, the maximum occurring at  $\log \tau_{\text{Ross}} = -2$ .

Thus the resultant Cayrel effect is small for C I in RCB stars with a temperature increase less than 10 K at the top of the photosphere. This micro-chromosphere does not alleviate the carbon problem! The small Cayrel effect is partly linked to the fact that carbon atoms are not totally dominating the scene. In fact at these relevant depths photoionization of carbon atoms only contributes typically 50 per cent of the opacity. So, even drastic changes (at least reductions) to the carbon opacity only lead to moderate changes of fluxes and of the energy balance. Another circumstance is that the ultraviolet flux in the surface layers is so weak that it does not seem to matter very much and is unlike the situation for hot stars and the H I opacity; only a tiny fraction of the flux of typical RCB stars comes at energies higher than the ionization threshold, or even at energies able to photoionize from lower excited C I levels.

### 6.3 Hand-crafted models

The fact that the carbon problems defined by the C I and the [C I] lines are very similar from star to star across the sample of analysed RCB stars implies that the problems' resolution cannot depend very sensitively on a star's individual characteristics. Departures of the atmospheric structure from that predicted by a standard (MARCS) model must be very similar across the sample of stars. If departures are attributable to deposition of mechanical energy, the flux of mechanical energy cannot vary widely across the sample.

That the atmospheric structure is partly the culprit is suggested by the observation that an RCB star in a decline shows a reduced carbon problem. The case of V482 Cyg was discussed in Section 5.8. There, the carbon problem for the C I lines vanished. Note that the C I lines are noticeably stronger in our spectrum than in spectra taken at maximum light. The problem remains for the 9850-Å forbidden line, but this might be the result of overlying emission, as occurred in the case of RY Sgr. (Unfortunately, the 8727-Å line was not on the recorded spectrum.) A similar strengthening of C I lines leading to elimination of the carbon problem but with retention of the problem for the [C I] 9850-Å line was seen by Rao et al. (1999) for R CrB in decline.

#### 6.3.1 The photospheric temperature gradient

The carbon problem may be related to an incorrect representation by the MARCS RCB star models of the temperature gradient through the region of line formation; a steeper/shallower gradient produces a stronger/weaker line. In this connection, it may be noted that Lambert & Rao's (1994) abundance analysis used unblanketed model atmospheres (Schönberner 1975) and found fair agreement between the observed and calculated equivalent widths of the C I lines. Note that the small carbon problem of 0.2 dex might be attributed to a combination of identifiable uncertainties. The primary factor responsible for the negligible carbon problem is that Schönberner's

unblanketed models have a shallower temperature gradient in the line-forming region than the MARCS (line-blanketed) RCB star models (Gustafsson & Asplund 1996).

Unblanketed models were calculated with the MARCS code. Our abundance analysis for R CrB using unblanketed MARCS models shows that the carbon problems presented by permitted and forbidden C I lines are similar for unblanketed and blanketed MARCS models. The carbon abundance derived from the [C I] 9850-Å line using unblanketed models again agrees with that from the C I lines. The large difference between the carbon abundance derived from the [C I] 9850-Å line and the [C I] 8727-Å line using the blanketed models is unaltered by using the unblanketed models. The difference between the unblanketed MARCS and Schönberner's models reflects differing temperature gradients of the models.

Asplund et al. describe hand-crafted adjustments to the line-blanketed models that reduce the photospheric temperature gradient and alleviate the carbon problem presented by the C I lines. A shallower gradient (with respect to a blanketed MARCS model) was qualitatively justified as arising from deposition of mechanical energy the source of which may be the sub-photospheric convection zone. Examples of temperature-modified models, which alleviate the carbon problem from C I lines, were kindly provided by Martin Asplund (private communication). Our analyses using these models show that the carbon problem vanishes for the 9850-Å [C I] line as it does for the C I lines, but the 8727-Å [C I] line continues to present a problem; the carbon abundance from the 8727-Å [C I] line is about 0.7 dex less than that from the 9850-Å [C I] line, a difference found also for unmodified line-blanketed and unblanketed models.

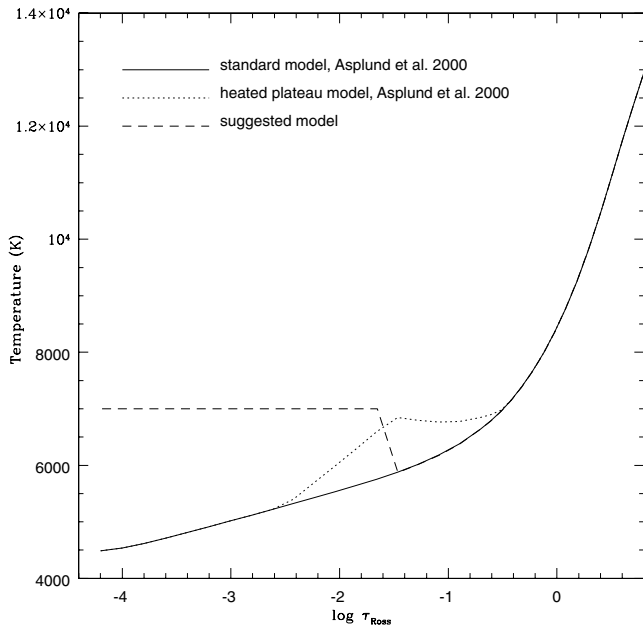
#### 6.3.2 A chromosphere

Addition of a temperature rise ('a chromosphere') at the top of the photosphere may also modify the predicted strengths of the absorption lines in the emergent spectrum. The chromosphere must be crafted by hand without theoretical guidance, but mindful of the discussion in the previous section.

Experiments were carried out by adding a chromosphere to a MARCS line-blanketed model. Fig. 5 shows one experiment appropriate for R CrB itself. A temperature rise is introduced at  $\log \tau_{\text{Ross}} = -1.6$ . A flat temperature profile of 7000 K in the interval  $\log \tau_{\text{Ross}} \leq -1.6$  and an LTE spectral synthesis reproduce the profiles of the observed [C I] 9850- and 8727-Å absorption lines. The two lines now return the same C abundance which is equal to the input abundance, or, put another way, the carbon problem vanishes for these lines. The weaker observed C I lines are also reproduced with the input abundance. Very strong C I lines are predicted, as expected for an LTE calculation, to have emission cores. The emission cores might be reduced if the non-LTE effects are taken into consideration. Quite obviously, the chosen chromosphere is not a unique solution. If the onset of the sharp temperature rise is placed as in Fig. 5, a chromospheric temperature of 6750 to 7000 K provides acceptable solutions to the carbon problems. Similar chromospheres remove the carbon problems for the other RCB stars. The chromospheric temperature may scale with the effective temperature of a star, but the range of sampled effective temperatures is small.

Addition of a chromosphere changes not only the predicted strengths of the C I and [C I] lines but also the predicted strengths of other lines and, therefore, the derived abundances. High-excitation lines such as the N I line at 8729 Å are so weakened by chromospheric emission that the observed absorption line in XX Cam and





**Figure 5.** Three  $T$ - $\tau_{\text{Ross}}$  structures are shown – see key at the top of the figure. The solid line shows a MARCS model for  $T_{\text{eff}} = 6750$  and  $\log g = 0.5$ . The modified  $T$ - $\tau$  structure with a heated plateau devised by Asplund et al. (2000) to eliminate the carbon problem for C I lines is shown by the dotted line. Our model with a chromosphere is shown by the dashed line.

RCrB cannot be fitted whatever the adopted nitrogen abundance. Although careful crafting of the chromospheric temperature profile may alleviate this difficulty, it seems likely that a non-LTE synthesis may be necessary. One may need to adopt a spherical rather than a plane-parallel geometry. The chromosphere, if it exists, is likely to be highly structured and a far cry from the homogeneous plane-parallel (or spherical) layers assumed for the models.

Although the artifice of a chromosphere serves to reduce or even eliminate the carbon problems, its presence presents another puzzle. The energy flux needed to produce the extra heating suggested here is substantial. Following Asplund et al. (2000), we find it to be of the order of 10–15 per cent of the total stellar flux. For comparison, the chromospheric–coronal heating of normal late-type stars is limited to about 1 per cent of the total bolometric flux. A clue to the problem may lie in the very large widths of RCB star lines – compare the widths of lines (Figs 1 and 2) in  $\gamma$  Cyg and the RCB stars. These large widths imply a very turbulent atmosphere and dissipation of energy. The possibility of an external radiation field generating the very large RCB star linewidths needs to be explored.

Emission lines appear when an RCB star goes into decline. The emitting gas is not necessarily to be identified with the hand-crafted chromosphere. Emission from a shell around the star would dilute the photospheric absorption lines. Emission in the 9850- and 8727-Å lines might weaken the absorption lines such that the emission is not seen but the weakened absorption lines return different carbon abundances. The [C I] lines are seen in emission in spectra taken in decline (Rao & Lambert 1993; Rao et al. 1999). The measured fluxes in decline are possibly lower limits to the fluxes at maximum light as the dust cloud responsible for the decline presumably obscures parts of the emitting shell. At maximum light, the cores of the strongest low-excitation absorption lines of singly ionized metals appear distorted by emission (Lambert, Rao & Giridhar 1990; Rao et al. 1999). It is just such lines which are prominent in the emission-line spectrum. The emission-line spectrum is of low exci-

tation and does not include the C I lines. Therefore the emitting shell which may contribute to the [C I] problem is not a player in the C I problem. In this context, it is relevant to recall the case of V482 Cyg observed below maximum light where the carbon problem is absent for the C I lines but not for the [C I] 9850-Å line. Our speculation is that the emitting shell fills in the forbidden line and the photospheric temperature gradient is steeper than at maximum light.

## 7 CONCLUDING REMARKS

The intriguing carbon problem presented by the RCB stars was discovered by Asplund et al. (2000) in an application of MARCS RCB star models to analysis of C I lines. Our contribution to the problem has been to present and analyse observations of the [C I] 8727- and 9850-Å lines, also with the MARCS models. The 9850-Å line presents a problem of similar magnitude (about 0.6 dex) to C I lines, but the carbon problem presented by the 8727-Å line is more severe by about 0.7 dex than the original problem (about 0.6 dex).

The fact that the carbon problems defined by the C I and the [C I] lines are similar from star to star across the sample of analysed RCB stars implies that the solution cannot depend on the individual characteristics of a star. Departures of the atmospheric structure from that predicted by a standard (MARCS) model must be similar across the sample of stars. If departures are attributable to deposition of mechanical energy, the flux of deposited mechanical energy cannot vary widely across the sample.

Uncovering the carbon problem was a surprise. Confidence in model atmospheres was shaken. Extension of the problem to the [C I] lines is also disconcerting. In spite of the fact that the RCB stars in several ways are very complex, they have the one property that should make the analysis of C I lines in principle simpler than for almost all other stars. This is the fact that the lines and the dominant opacity source are due to the same element with the lines and the opacity originating from levels of similar character and excitation. This provides a test that is not offered for other stars. This test, however, fails.

Perhaps the problems are restricted to very peculiar stars such as the rare RCB stars, but this supposition deserves to be tested. Luminous normal (i.e. H-rich) supergiants of the temperature of the RCB stars are the stars from which chemical compositions of external galaxies are now being derived. Are their atmospheric structures reliably simulated by our codes? Or is there a problem analogous to the carbon problem awaiting discovery?

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