Model atmospheres for cool hydrogen-deficient carbon stars

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Abstract. A grid of line-blanketed, hydrogen-deficient and carbon-rich model atmospheres, with effective temperatures ranging from 5000 K to 9500 K, surface accelerations of gravity in the interval from 0.3 to 100 cm s$^{-2}$, and chemical compositions characteristic of R Coronae Borealis stars is presented. The models show steep temperature gradients caused by the heavy line blanketing. This makes the models reproduce the occurrence of both C$_2$ bands and C I lines in the same stellar spectra, as well as the fact that the He I D$_3$ line is visible in photospheric spectra with $T_{\text{eff}} > 6500$ K. Also, the overall flux distribution of R CrB itself is well reproduced. The failure of the models to account for observed C I line strengths, which are predicted to be too strong, is discussed. The models show density inversions in the deep layers, and the low gravity models also show gas pressure inversions. Consequences of these are discussed separately in the present volume (Asplund & Gustafsson)

1. Introduction

Attempts to solve the basic remaining problems concerning the nature of the R Coronae Borealis (RCB) stars — the reasons for their sudden declines in brightness and their unclear evolutionary stage(s) — are dependent on estimates of the fundamental parameters of these stars, i.e. effective temperatures, masses, luminosities, surface accelerations of gravity, and chemical compositions. In order to estimate these parameters adequate model atmospheres are needed. The only previous grid of models that exists is 20 years old (Schönberner 1975) and is based on by now outdated opacity data as regards continuous absorption and the important spectral line-blanketing is not accounted for. Recent progress in these respects, as well as the need for adequate analysis of new spectroscopic data of unprecedented quality (see Lambert and Rao 1994, Rao 1996 and Lambert et al. 1996) motivate the construction of a new grid of model atmospheres. In the present paper such a grid is described and its successes and shortcomings

2. The grid

The models of the grid are classical in the sense that the standard basic assumptions are made: plane-parallel stratification, hydrostatic equilibrium, local thermodynamic equilibrium (LTE) and constancy of the total flux, with the contribution from convection calculated according to the so-called mixing-length
Figure 1. The continuous opacity (Rosseland weighted) as a function of $\tau_{\text{Ross}}$ for a typical model ($T_{\text{eff}} = 7000$ K, $\log g = 0.5$ (cgs) and $C/\text{He} = 1\%$) for the most important contributors. The total Rosseland mean opacity is given by the solid line. Notice the dominance of electron scattering in the outermost layers, C1 bf in the line-forming region and He1 bf at depth. For very small $C/\text{He}$ ratios He$^-$ takes over as the main opacity source.

theory. The probable effects of departures from these assumptions in real stars are studied by relaxing some of them, one at a time (see below) in the model calculations.

The most important improvement of the present models, as compared with those of Schönberner (1975), is the use of modern opacity data. The bound-free continuous absorption from H I and H$^-$ and from atoms and relevant ions of He, C, N, O, Mg, Al, Si, Ca and Fe, is included and mainly based on data from the Opacity Project (Seaton et al. 1994 and references therein). In addition to this free-free absorption from H I, He I, C I, C II, H$^-$, He$^-$, C$^-$, N$^-$, and O$^-$ is included, as well as electron scattering and Rayleigh scattering from He I and C I. The dominating continuous absorption is due to C I, electron scattering in the outer layers and He I in the deep layers of the model atmospheres, see Fig 1. A number of spectral lines (bound-bound transitions) of C, Na, Al, Mg and Si with gf-values from the Opacity Project (Seaton et al. 1994) and Wiese et al. (1969) are included, as well as a wealth of lines of heavier elements (Ca - Ni).

The line absorption is represented by opacity sampling for wavelengths shorter than 450 nm (in 5000 wavelength points) and by opacity distribution functions (ODF's) for wavelengths longer than 450 nm (in 500 points). The numerical method used is a complete linearization scheme described by Edvardsson et al. (1993), which produces rapidly converged solutions, also close to the Eddington limit. The code is an extension of the original MARCS code (Gustafsson et al. 1975).
The line-blanketing effects are dependent on the line absorption divided by the continuous absorption, $l_\nu/k_\nu$. Typically, this ratio is about a factor of 5 greater for the hydrogen-deficient models of the grid than for corresponding model atmospheres with solar abundances. This reflects the lower continuous absorption, due to the drastically reduced hydrogen abundance (see below).

The parameters of the grid are chosen such that $5000 \leq T_{\text{eff}} \leq 9500$ K, $-0.5 \leq \log g \leq 2.0$ (cgs units) and, for most models, a standard chemical composition is adopted, following the spectral analysis results of Lambert and Rao (1994). The C/He abundance ratio, which is not known for RCB stars, is for most models set to 1%, in accordance with determinations for extreme helium (EHe) stars (Heber 1986); in addition to this sets of models have been calculated with four alternative C/He ratios (0.1% - 10%). The microturbulence parameter is chosen to 5 km s$^{-1}$. Altogether, 137 models have been calculated for the grid described here.

Improvements regarding line-blanketed spherical models and the opacity is in progress. This will allow hydrogen-deficient models to be computed for an expanded range in fundamental parameters, in particular towards more extended atmospheres and for higher temperatures.

3. Physical properties of the models

The run of basic thermodynamic parameters with optical depth for models of three different effective temperatures is shown in Fig. 2. It is clear from these curves that the structural variations with effective temperature cannot be reproduced by simple scaling laws. A physically interesting phenomenon is shown in the second and third panels – obviously there is a density inversion for all three models in the deep layers and, for the hottest model, even a gas pressure inversion. These inversions, which are further discussed by Asplund and Gustafsson (1996) in the present volume, reflect the strong gradient in the radiative pressure – in turn the result of the steep temperature gradient with He I absorption as a major temperature-sensitive absorber in the helium ionization zone in the deep atmospheric layers. The great effects of line blanketing are displayed in Fig. 3. Obviously, the surface cooling caused by the spectral lines may amount to almost 1000 K, and the back-warming may even be greater.

In Fig. 5 the predicted flux distribution of a model with parameters not very far from those of the eponymous star R CrB itself is compared with the observations of that star. In the optical comparison is made with unpublished, dereddened, narrow-band photometry kindly provided to us by N.K. Rao, while the infrared data has been taken from Glass (1978). The overall agreement is clearly satisfactory with a model with $T_{\text{eff}} = 7000$ K. In particular, the ability of the model to reproduce the overall flux distribution in the ultraviolet is gratifying when comparing an IUE spectrum taken at similar pulsational phase as the optical data with the model fluxes (Fig. 5b). Note that the model flux longwards of 450 nm is characterized by the "giant lines" of the ODFs; the blocking of these lines should be adequate within each ODF wavelength interval, but the line absorption within each such interval is in real stars much more distributed.

Another success of these models is the fact that the observed C$_2$ Swan bands, such as the (0,1) band at 563.5 nm, are well reproduced with reasonable effective
Figure 2. Atmospheric structures of three models with different effective temperatures: $T_{\text{eff}} = 6000$ (solid), 7000 (dotted) and 8000 K (dashed), all with $\log g = 0.5$ (cgs units), $\xi_{\text{turb}} = 5 \text{ km s}^{-1}$ and C/He = 1%. The different panels show temperature, density, gas pressure and electron pressure, vs Rosseland mean optical depth, respectively. The density inversions and the gas pressure inversion for the high temperature model at great optical depths should be noted.
Figure 3. The differential effects of line blanketing shown for a model with $T_{\text{eff}} = 7\,000$ K, $\log g = 0.5$ (cgs units), $\xi_{\text{turb}} = 5\,\text{km\,s}^{-1}$ and $C/\text{He} = 1\%$. The difference between the temperature of an unblanketed model, and that of a blanketed one is shown as a full curve; similarly the lower panel displays the ratio of the pressures of these two models, with the reference model being the line-blanketed one.
Figure 4. One of the grid models presented here (solid) in the temperature-pressure plane as compared with the corresponding (unblanketed) model of Schönberner (1975) (dashed). Logarithmic Rosseland optical depths are marked along the curves. The great effects of line-blanketing are clearly seen.
Figure 5.  

a) Comparison of measured fluxes of R CrB with fluxes of a model with $T_{\text{eff}} = 7000$ K and $\log g = 0.5$ (cgs units). The triangles denote narrow-band visual fluxes from N.K. Rao (private communication) and infrared magnitudes (J and H) from Glass (1978). The dashed line represent the ultraviolet fluxes obtained from the IUE Ultraviolet Low Dispersion Archive (observations of August 17, 1979). In b) a close-up of the UV region is shown.
temperatures, as are the C II and He I lines. This fact, which is further discussed by Lambert et al. (1996) (see also Rao 1996), is a natural consequence of the steep temperature gradient which allows C_2 bands to form in the surface layers while C II lines are formed deeper in the same models. Similarly, even the He I D_3 line at 578.6 nm, which is blended by C I lines, contributes significantly to the blend already for T_{eff} \sim 6500 K in RCB models and reproduces the observations very satisfactory - again an effect of the steep temperature gradient (see Lambert et al. 1996). However, a major problem of the present models is the lack of agreement between predicted and observed C I line strengths.

4. The C I line dilemma

The C I absorption lines in the yellow-red spectral region of the model atmospheres are predicted to be considerably stronger than the observed lines for all RCB stars analyzed (17 stars in total) – the mismatch corresponds to a factor of 2 - 5 in abundance. These lines have high lower excitation energies (of typically 9 eV) and are mostly on the flat (microturbulence sensitive) part of the curve of growth. The mismatch seems to have a non-trivial explanation and it is a rather robust finding, not very sensitive to model errors etc. This is because the dominating continuous opacity of the models is due to photoionization of C I, from levels at excitation energies higher than, but not far away from, the lower levels of the C I lines. Thus, the I_{\nu}/\kappa_{\nu} ratio is not very sensitive to details in the model structures, nor to adopted fundamental parameters of the stars or to the carbon abundance (as long as C I remains the dominating continuous opacity source). In fact, the discrepancy also exists with the old models of Schönberner but to a lesser extent due to the flatter temperature gradient without the line blanketing and the in general larger continuous opacities of Peach (1970) compared to Opacity Project (Seaton et al. 1994). The problem has led to a number of special studies. The following reasons for it have been consi

1. The absorption coefficients or the gf-values for the C I lines may be in error (typically a factor of 3 would be needed). The atomic data, both for the bound-bound and the most important bound-free (C I bf) processes, are taken from the same data set of high quality (the Opacity Project, Seaton et al. 1994) and we do not consider this explanation probable.

2. The carbon abundance may be considerably lower than the 1% of the helium abundance adopted here. If carbon is reduced by more than a factor of 30 the He^- absorption will take over, and the C I lines will diminish in strength. There is, however, observational evidence against this – the spectra show only small variations in C I line strengths from star to star while other spectral lines vary strongly (cf Rao 1996). Also, this lower C/He ratio will decouple the evolutionary state of the RCB stars from that of the hotter EHe stars.

3. An extra continuous opacity, disregarded from or underestimated in the model atmospheres, would weaken the predicted C I lines. This absorption would have to be of the same order of magnitude as the dominating C I absorption and extend across a wide spectral region in order to preserve the fit to the observed flux distribution. It should also belong to a species that does not show significant abundance variations relative to carbon, and it should have a temperature sensitivity of the same character as the excited C I lines, in order
to explain the constancy of the C\textsubscript{I} lines in the different spectra. We do not know of any absorption that could satisfy these demands. Also, the effects of a "veil" of weak spectral lines on the continua could be invoked, but here again the constancy of the effect from star to star or when the effective temperature varies poses severe problems.

4. Departures from LTE (which is assumed throughout the analysis) are natural candidate explanations and this has been investigated by Asplund and Ryde (1996) for atomic carbon. The effects are found to be very small and confined to optical depths smaller than \( \tau_{\text{Ross}} = 0.01 \) for a typical RCB model atmosphere. The non-LTE abundance corrections for the observed C\textsubscript{I} lines are less than 0.1 dex (typically 0.02 dex and both negative and positive). Thus, the direct effects on the line strengths of C\textsubscript{I} lines are expected to be unimportant. Since carbon is the most significant active constituent of these model atmospheres, delivering the dominant absorption and most of the electrons (helium is, except for at the greatest depths, an "inert element" which mainly only contributes pressure and density) we do not believe that non-LTE effects on the model structure will be very severe either.

5. The RCB stars have low surface gravities and probably dynamic pulsating surface layers. Therefore, they may well be extended such that the assumptions of plane-parallel stratification and hydrostatic equilibrium are unrealistic. In attempts to explore this possibility we have calculated spherically symmetric, though static and unblanketed, models. These models have typical atmospheric thicknesses of 5-10\% of the stellar radii, and surface temperatures lowered by a few hundred K only, which is far too little to severely affect the C\textsubscript{I} lines. The inclusion of line opacity in the spherical models is likely to further increase the extension but probably not enough to explain the C\textsubscript{I} anomaly, since the high excitation energies cause them to be formed at rather great depths, in spite of their strengths. This also means that very extended and still hot envelopes would be needed in order to cause the "filling-in" of the C\textsubscript{I} line cores by emission from the envelope (of which there is no obser

6. Partial redistribution by scattering off thermal electrons may be expected to broaden but also seemingly weaken the C\textsubscript{I} lines (and all other photospheric lines as well). Since the C\textsubscript{I} lines are formed at considerable atmospheric depths they could be affected by this process since the electron pressure is relatively high above these depths in the model atmospheres. We have calculated this smearing of the C\textsubscript{I} lines following Mihalas (1978) but found the available electrons to be too few by about a factor of 10 for this effect to be significant. However, during a decline in brightness, emission lines appear from which electron densities of typically \( 10^9-10^{10}\text{ cm}^{-3} \) have been derived (e.g. Asplund 1995), and one may wonder whether these electrons can provide the necessary redistribution. We estimate that the above number densities must extend to about 5 stellar radii in order to supply the needed column densities. However, many emission lines seen during a decline are narrow and he

7. Could there be other model-atmosphere errors, e.g. connected with the primitive description of convection and other dynamic phenomena in the deep layers of the atmospheres? In order to reduce the C\textsubscript{I} strengths by the amount desired a considerably decreased temperature gradient (by about a factor of two) in the line-forming region is needed. It remains to be explored whether convec-
tive overshoot or other flows and indirect consequences of these (inhomogeneities etc) could lead to that.

8. The microturbulence parameters used in the spectral analysis are obtained from requiring lines of, e.g., neutral iron of different strengths to give the same iron abundance. Typically, values around 8 km/s are obtained, i.e. somewhat higher than the value used in the calculation of the model atmospheres, which is an insignificant inconsistency. However, could there be a microturbulence gradient in the atmospheres, such that the parameter at the C\textsc{i} line forming depth is smaller than at the more shallow depth where the Fe \textsc{i} lines are formed? Numerical experiments have proven that this explanation is hardly viable – the atmospheric formation regions for these two sets of spectral lines are close enough and partly overlapping, so that a factor of 3 difference in C\textsc{i} line strengths cannot be accomplished with any physically reasonable ad-hoc variation of the microturbulence parameter.

9. A continuous emission from the outer stellar atmosphere, e.g. from a hot dust envelope, could also be the reason for the C\textsc{i} problem. This emission, however, has to contribute at least 20\% of the stellar flux in the yellow-red, and it has to be so hot that it does not lead to emission in excess of that observed in the infrared. It is still unclear whether this could be a viable explanation; if so, it would imply that almost all RCB stars have dusty clouds at small distances from the stellar surfaces. Furthermore, the fit of the flux distribution for R CrB would be affected if there is significant contribution from circumstellar material in the visual (the observed C\textsc{i} are located around 600 nm).

5. Conclusions

The new model atmospheres have proven to reproduce different observed properties of RCB stars, and have also led to interesting suggestions concerning the origin and the triggering of the sudden declines of brightness (cf. Asplund and Gustafsson, 1996). These accomplishments are directly connected with our inclusion of the heavy blanketing in these models, reflecting the low continuous absorption. However, an apparently non-trivial discrepancy remains in the predicted line-strengths of the C\textsc{i} lines. Relatively severe changes in the basic assumptions of the models or the spectra are needed to explain this short-coming. As long as this situation is not clarified, conclusions based on the new models as applied in, e.g., abundance analysis must be regarded preliminary, though estimates of abundance ratios will be less uncertain. However, the C\textsc{i} line dilemma may also well contain interesting physical information as regards these enigmatic stars, still keeping interesting secrets away from revelation.

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Figure 6. Problems remain – as with the smiling queen on Unterenbrücke in Bamberg