Publ. Astron. Obs. Belgrade No. 75 (2003), 45 - 52 *Invited lecture*

R CORONAE BOREALIS STARS

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Abstract. Photometry and low- to high-resolution spectroscopy data have been obtained throughout six declines of different R Coronae Borealis (RCB) stars. Various emission lines which are typical of an RCB decline have been observed. The low-excitation lines, with a blue shift of a few $\mathrm{km\,s^{-1}}$ have been classified into E_2 group. The high-excitation lines of CI, OI and MgI, classified as E_1, exhibit a redshift of a few $\mathrm{km\,s^{-1}}$ relative to the stellar velocity, indicating a possible photospheric origin. The broad lines (BL group) show a constant absolute flux throughout the decline phase and therefore the region of their origin does not seem to be obscured by the dust cloud causing the decline. One can say that the line evolution is consistent with the classification into three groups according to the E_1/E_2/BL line region model, but they can have different origins from that suggested by the model.

1. INTRODUCTION

R Coronae Borealis (RCB) stars belong to a rare class of variable stars exhibiting quite unique variability. Their spectacular light fadings occur at irregular intervals, when the star declines rapidly by up to six magnitudes in a few weeks. The recovery to normal light is significantly slower and may take months, or even years. The characteristic light curve of RCB stars distinguishes these objects from other classes of variable stars.

In spite of the fact that RCB stars are so rare (only about 40 are known in our Galaxy), there are many reasons for investigating them. Both the unique nature of the RCB variability and their evolutionary status remain unsolved. Only a relatively small number of extensive spectroscopic studies of RCB declines can be found, mainly owing to the irregularity and unpredictability of the decline events. Only a few declines of the brightest RCB stars have been monitored completely: one decline of RY Sgr (Alexander et al. 1972) and two declines of R CrB (Cottrell et al. 1990, Rao et al. 1999).

In order to provide simultaneous photometric and spectroscopic coverage throughout the decline of RCB stars, an extensive observing programme has been organized at Mt John University Observatory (MJUO) and the Department of Physics and Astronomy, University of Canterbury (Cottrell 1996). A number of RCB declines (S Aps, RZ Nor, V854 Cen, RS Tel, UW Cen and V CrA) observed at MJUO will be presented in this paper. The 1998 decline of V854 Cen represents the first almost complete coverage of a decline for this star (Skuljan & Cottrell 2002). The evolution and physical characteristics of various lines appearing during the decline will be discussed. A review of the existing observational data and the most popular theoretical models will also be given.

2. R CORONAE BOREALIS STARS: WHAT DO WE KNOW?

A majority of the RCB stars spectroscopically look like F–G supergiants, with effective temperatures of about 7000 K, but with relatively strong carbon lines and either weak or absent hydrogen lines (Clayton 1996). The absolute brightness, M_V, in the range from -4^{m} to -5^{m}, was determined from a few RCB stars in the LMC (Feast 1979). These stars belong to low-mass objects, with a typical value of $0.8 - 0.9\ M_{\odot}$ (Weiss 1987).

The evolutionary status of RCB stars still remains unsolved. There are two generally accepted models: FF (**F**inal Helium-Shell **F**lash) and DD (**D**ouble **D**egenerate) models. In both of them, RCB stars are considered to be new-born supergiants, that have already started their final evolution toward the white dwarf stage. The FF model (Renzini 1990) suggests that these stars originate from a white dwarf experiencing a final helium-shell flash. On the other hand, the DD model (Webbink 1984) is based on a merging process of a close binary system of He and CO white dwarfs. However neither of the two models mentioned above provides a completely satisfactory agreement with observations.

There are a few of observational facts, that provide some important characteristics of RCB stars. First, they all show a variability at light maximum, with typical periods between 40 and 100 days. It is believed that these variations are due to stellar pulsations (Clayton 1996). Second, the infrared photometry of these stars shows a clear IR excess due to a circumstellar dust (Feast 1979). During the decline the total flux level does not change, indicating that only a small amount of dust is produced in any one decline and the dust does not form as a complete shell around the star. However, since all RCB stars show a significant IR excess, this suggests that there is a large amount of dust produced around the star through a number of dust formations occurring off the line of sight. Third, during the decline, as the total intensity of the photospheric spectrum decreases, a rich emission line spectrum appears.

The most generally accepted explanation of the RCB declines is based on the obscuration of the stellar photosphere by the dust cloud (Loretta 1934). A dust cloud is occasionally formed somewhere around the star and accelerated due to radiation pressure. When the cloud forms along the line of sight it will obscure the star and a decline will start. Many observational facts and theoretical calculations support the dust cloud hypothesis. This scenario can explain very well the existence of light curves with different shapes, depths and durations. However, the question of where and how the dust cloud forms and accelerates still remains unsolved. In general, two different approaches have been considered: a dust cloud forming far from the star, at about $20R_*$, or close to the star, at about $2R_*$. Neither of the two models are completely accepted. However some recent theoretical calculations of the condensation temperature of carbon in non-LTE (Woitke et al. 1996) provide some facts in favor of the $2R_*$ model. The changes in the photospheric absorption spectra were observed prior to the decline, indicating that the triggering mechanism might be connected to the shock wave propagating through the atmosphere (Rao et al. 1999).

All emission lines appearing during the decline can be classified into three groups: E_1, E_2 and BL (Alexander et al. 1972), according to their evolution, so that the shortest lived lines are from the E_1 group, then the E_2 lines stay visible longer throughout the decline and the BL group includes broad lines. The fading of emission lines during the decline phase makes sense if the star is surrounded by three distinct emission regions responsible for the E_1, E_2 and BL emissions. The E_1 region, being closer to the star ($1.5R_* - 2R_*$) is obscured first. This is then followed by the obscuration of the E_2 and BL regions found at somewhat larger distances of about $10R_*$.

3. OBSERVATIONS AND DATA ANALYSIS

A total of six declines of different RCB stars were observed during the observing programme of two and a half years (four were covered completely and two partially). The observations included photometry with an 0.6-m telescope and spectroscopy with the 1-m telescope. Regular photometric observations were part of the long-term monitoring of these stars at MJUO. They provide *UBVRI* photometry and also serve as an indicator of a decline. Intensive spectroscopic observations have been made using either the medium-resolution (resolving power R between 2000 and 10000) or the échelle spectrograph ($R \sim 30000$) during the decline phases of the programme stars and, less intensively, at light maximum. Some observations were also obtained at McDonald Observatory, Texas, with the 2.7-m telescope and a resolving power of 60000.

Observed declines had different duration and depth. The shallowest was one magnitude deep (RS Tel) while the deepest was about 7 magnitudes deep (S Aps). The shortest was about 3 months long (RZ Nor) and the longest about 4 years and was only partially covered (UW Cen). The majority of them show complex light curves with a number of fadings and partially recoveries. An example of one of the observed declines of V854 Cen is shown in Fig. 1. This star is one of the most unusual of all RCBs with high frequency of declines and a hydrogen-rich atmosphere, when compared to other RCB stars. Fig. 1 also shows complex colour variations, which are always observed during the decline, especially during the recovery phase.

Our aim was to measure the line parameters (radial velocities, equivalent widths and absolute fluxes) for as many as possible spectral lines and throughout the whole decline phase, so that the evolution of the spectral lines and their characteristics can be examined. All techniques that have been used can be classified into four main groups: subtraction procedure, flux calibration, measuring the line parameters and modelling of complex NaI D profiles (Skuljan 2001).

4. LINE CLASSIFICATION

All lines appearing during the declines have been classified into three main groups: sharp emission lines, broad emission lines and high-velocity NaI D absorption.

Sharp emission lines are slightly broader then the instrumental profile of $5 - 10$ km s^{-1} for the high resolution spectra. They include the low excitation lines with the upper excitation potential of less than 5 eV (such as BaII, ScII, FeII and

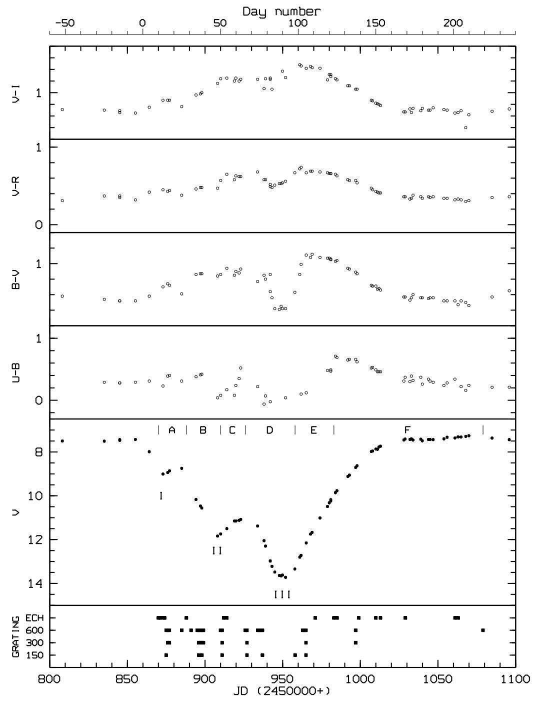

Figure 1: The visual magnitude (V) and colours: $(U-B)$, $(B-V)$, $(V-R)$ and $(V-I)$ during a typical RCB decline. Day numbers (top axis) are measured from the beginning of the decline (JD 2450860). The times at which the spectroscopic observations were made are also marked (black squares in the lower panel).

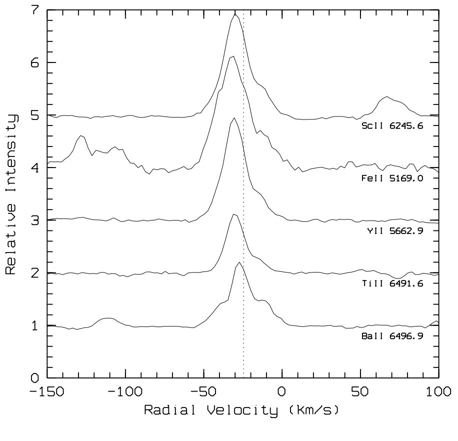

Figure 2: Selected sharp emission lines of singly-ionized elements, blue-shifted relative to the systemic velocity (dashed line).

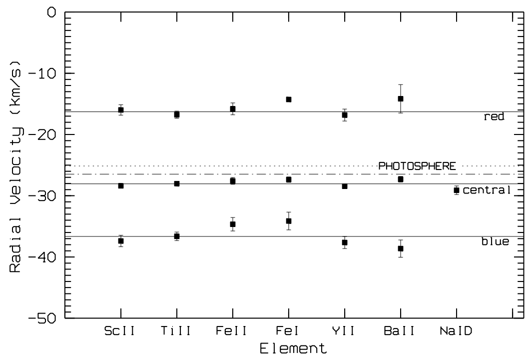

Figure 3: Radial velocities of different atomic species derived from a number of low-excitation sharp emission lines (the 1998 decline of V854 Cen).

others), then the high excitation lines with the upper excitation potential of about 10 eV (CI, OI and MgI), molecular bands of C_2 and the forbidden lines.

The low excitation lines exhibit a typical time scale of the E_2 group and have been observed through the whole decline. They show a multi-component structure with one central and two weaker and somewhat broader side components (Fig. 2). The central component is blue shifted by about a couple $\mathrm{km\,s^{-1}}$ relative to the photospheric velocity, marked with a dashed line in Fig. 2.

Three Gaussians have been fitted to each of these lines and the radial velocities and equivalent widths of the components have been found. Fig. 3 shows the radial velocities of three components for different atomic species. Each point is an average of a number of lines of the given element. Three horizontal solid lines represent the mean velocity of each component derived from all elements. The systemic velocity is marked by a dotted line and the average velocities of the blue and red components by a dash-dotted line. It can be shown that the arithmetic mean of the blue and red components is closer to the photospheric velocity than to the velocity of the central component. This could mean that the spectral lines originate from two different shells surrounding the star and expanding with different velocities. The blue and red components may belong to the outer shell (expanding faster), so that they are coming from regions moving toward and away from the observer, respectively. On the other hand, the central component may originate from a slower-moving inner shell, so that the corresponding two components cannot be resolved.

Results also show that the velocities of the low-excitation lines are independent of the upper excitation potential and remain the same throughout the decline, indicating that there is no interaction between the dust cloud and the emitting region. The fluxes of these lines have been derived from the flux calibrated spectra using the observed *UBVRI* magnitudes (Skuljan & Cottrell 2002). They have been used for studying the interaction of lines with the dust cloud. It was found that the line fluxes do not decline in step with the photospheric flux (the continuum is decaying about ten times faster then the line fluxes). The lines show a constant flux at the beginning of the decline. After that, the line fluxes decrease slowly, indicating that the emission line regions probably become obscured by the dust cloud. The excitation temperature

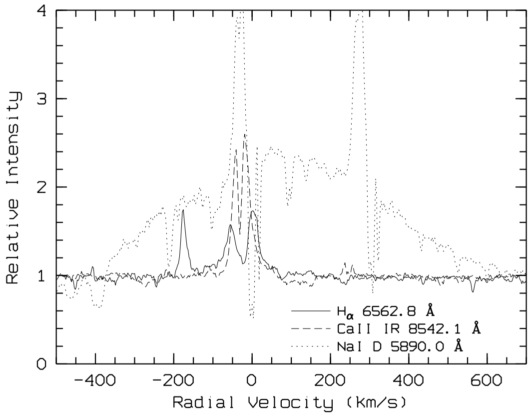

Figure 4: The H_α line and the CaII IR triplet compared to the broad NaI D emission. Other components of NaI D lines can also be seen.

of $T_{\rm exc} = (5600 \pm 800)$ K for the low excitation lines have been estimated from the Boltzmann plot of TiII spectral lines.

On the other hand, the high-excitation lines (CI, OI and MgI) have been observed only during the initial stages and classified as E_1. The lines show only one single profile and are red shifted by about a couple $\rm km\,s^{-1}$ relative to the stellar velocity.

5. NaI D LINES

The NaI D lines were especially observed and studied throughout this work, since this element is quite abundant in RCB stars and the lines are strong and very easy to observe in almost all RCB declines and throughout the whole decline phase. In addition to the standard components (photospheric, interstellar and sky), the NaI D lines exhibit an interesting evolution of a number of other components during the decline phase: sharp emission, broad emission, high-velocity blue-shifted absorption and shell absorption. A special procedure was developed for fitting the complex NaI D lines (Skuljan 2001).

Fig. 4 shows that the broad NaI D lines are much stronger than the $H\alpha$ and CaII IR broad emission. Observations also show that the broad NaI D lines are visible throughout the whole decline phase. They have different strengths from one RCB star to another. For example, for S Aps the broad emission is at a very low level of 10% to 15% of the continuum, while for V854 Cen it is much stronger. Actually, when a more detailed analysis is made, we find that the strongest emission is detected in the star with the most frequent declines, such as V854 Cen, which has declines almost every year. This can mean that the significant amount of gas formed in each of the decline is responsible for the broad emission as well. It was also found that the flux of these lines throughout the decline stays constant, indicating that the emitting region is not affected by the dust cloud.

One of the most interesting features of the decline phase is the high-velocity blue shifted absorption (HVA), identified only in NaI D lines. These absorption lines, at

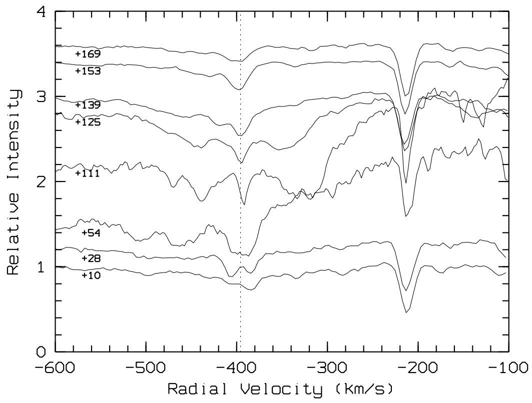

Figure 5: The evolution of the NaI D_2 high-velocity absorption throughout the decline. The vertical dashed line is placed at the position of the central component of the recovery phase spectra. The strongest component of the initial phase (day number +10) appears red-shifted with respect to this line.

velocities between $-400\ \mathrm{km\,s^{-1}}$ and $-230\ \mathrm{km\,s^{-1}}$, were observed in all declines. Fig. 5 represents a typical evolution of the HVA. At least three components can be recognized during the initial phase. The strongest of them remains visible throughout the whole decline. During the deepest minimum, the HVA profile becomes quite extended, so that the components become difficult to resolve. During the recovery phase the HVA exhibits a sharp and well distinguished central component, with a few broad absorption profiles on both sides.

Relatively high radial velocity of these lines means that they have a circumstellar origin. They also have never been observed or identified at the light maximum indicating that they can be attributed to the gas accelerated during the process of the dust cloud formation.

When the HVA is analysed as a singe complex profile, a constantly increasing blue shift is detected throughout the recovery phase. This can be interpreted as an acceleration of the gas. The acceleration was obtained in the range between $0.5\ \mathrm{cm\,s^{-2}}$ for S Aps (Skuljan 1999) and $2\ \mathrm{cm\,s^{-2}}$ for UW Cen. Using this acceleration, the position of the sharp emission lines region (E_2) can be estimated. Assuming that the dust cloud was formed at $2\,R_*$, and taking into account that the time when the sharp emission lines start decaying, the position of the E_2 region can be located between $3.0\,R_*$ and $5.0\,R_*$

6. CONCLUSION

Although all RCB declines observed have different durations and depths, they all show similar photometric and spectroscopic characteristics, indicating that common mechanism is responsible for all declines. All declines show a significant reddening, suggesting some kind of obscuration by the dust cloud.

Sharp NaI D components and low-excitation lines, according to their time scale, can be classified into E_2 group. They are typical features observed in all RCB declines with a small blue shift indicating that they originate from a material slowly moving away from the star with the excitation temperature slightly cooler then the photosphere. There is indication that they might be permanent features according to the identification of two of these lines, ScII and NaI D, at the light maximum by Rao et al. (1999). The low-excitation lines show multicomponent structure indicating existence of a shell. However this structure was identified only in two RCB stars and needs more studying for different stars and different declines. According to the small reddening it seems that the emitting region is not affected by the dust cloud in the same way as photosphere and is still exposed to the photospheric radiation. The line flux decay indicates that the position of this region can be located between 3 and 5 stellar radii.

On the other hand the high-excitation lines of CI and OI, according to the time scale, can be classified into E_1 group, but they show a red shift that can be interpreted as an indicator of the shock triggering the decline onset. Therefore, their real origin can be in the photosphere.

Broad NaI D lines show a constant flux from one decline to another, which can be an indicator of their permanent nature, as well as a constant flux throughout the decline, which means that they are not affected directly by the dust cloud.

The high-velocity NaI D absorption is a typical feature of all RCB declines, observed only during the decline, with a high radial velocity, and can be associated with the gas formed during the process of the dust cloud formation. These lines show a typical evolution and profile in all declines.

As a final concluding remark, our observations show that most spectral lines (but not all of them) can be classified into three groups according to their *evolution*. However, they do not necessarily have to originate from the three distinct regions, as suggested by the E_1/E_2/BL model.

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