The optical spectrum of R Coronae Borealis close to 2003 decline

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Abstract. Two sets of high-resolution spectra of R CrB obtained during the 2003 light decline are described. The first set was obtained on the descending branch of the light curve when \( V \approx 12.0 \) and the second one in the recovery phase with \( V \approx 7.5 \). The usual sharp and broad emissions are described and the lines radial velocities measured. \( \text{C}_2 \) Swan system (0,0) band was found to be in emission for the first set. The other \( \text{C}_2 \) bands were in absorption. Few CN red system (5,1) band rotational lines and low excitation Fe I lines were in absorption. A table with measured radial velocities of various spectral features is presented.

Key words: stars: atmospheres – stars: individual: R CrB

1. INTRODUCTION

R CrB is the prototype of peculiar supergiant stars with fast and deep dimmings by several magnitudes at unpredictable times. These dimmings last several weeks or months. The atmospheres of R CrB type stars are extremely hydrogen deficient and carbon rich. The light minima are believed to be caused by the formation of obscuring clouds of carbon soot (O’Keefe 1939). About 30 stars of the class are known and the prototype is one of the most studied since its discovery 210 years ago. Due to unpredictability of the dimmings the spectral observations during the light minima are sparse. However, these observations could provide novel information about the outer stellar atmosphere and circumstellar region as the photosphere is almost completely obscured for several weeks before the soot cloud disperses.
In this note we report on spectra obtained during the 2003 light minimum of R CrB. Clayton (1996) gave a general review of R CrB spectra in and out of declines. Rao et al. (1999) studied the optical spectrum of R CrB in the very deep and prolonged minimum in 1995. The previous minimum of R CrB on 2000 was described by Kipper (2001). The 2003 minimum was also observed by Rao et al. (2006). Our spectra were obtained somewhat earlier and later and therefore well complement Rao et al. data.

In Fig. 1 the light curve of R CrB during the 2003 light minimum is shown (AAVSO data) and the moments of our (long vertical lines) and Rao et al. (2006) spectroscopic observations are marked. The first set of our spectra was obtained on February 24 with the star at $V \approx 12.0$ and the second one on April 11 when the star has recovered to $V \approx 7.5$. Finally, two sets of the spectra were obtained on January 12, 2004 and April 18, 2006 when the star has completely recovered.

2. OBSERVATIONS
All our high resolution ($R \approx 42\,000$) spectra were obtained with the Nasmyth Echelle Spectrometer (Panchuk et al. 1999; Panchuk et al. 2002) of Russian 6 m telescope. The spectrograph was equipped with an image slicer (Panchuk et al. 2003). As a detector a CCD camera with $2052 \times 2052$ pixels produced by the Copenhagen University Observatory was used. The first set, which was observed close to the light minimum and the last one at the maximum light cover the wavelength region $516.0 \div 666.0$ nm without gaps up to 600.0 nm. The set observed when the star’s brightness has almost recovered is shifted toward blue and covers $448.0 \div 600.0$ nm without gaps.

3. DESCRIPTION OF THE SPECTRA

3.1. Reduction of the spectra

The spectra were reduced using the NOAO astronomical data analysis facility IRAF. The continuum was placed by fitting low order spline functions through the manually indicated points in every order. The use of image slicer results in three parallel strips of spectra in each order. These strips are wavelength shifted. Therefore all strips were reduced separately and then already linearized in the wavelength spectra were coadded. We checked the accuracy of this procedure (Kipper & Klochkova 2005) and found that the wavelengths of the terrestrial lines in the stellar spectrum were reproduced within a few 0.001 Å-s. After that all spectra of the set were coadded.

As measured from the Th-Ar comparison spectra the resolution is $R \approx 42\,800$ with FWHM of comparison lines about 7 km s$^{-1}$.

As it was expecting for the spectrum of R CrB close to its minimum light, the spectrum by February 24 contains numerous emission sharp lines, the complex profile of Na I D lines including broad and sharp emissions, weak Hα emission, strong C I lines, the remarkable emission of forbidden [O I], the C$_2$, CN molecular bands. All these spectral features were considered below in detail.

It should be noted here that main abovementioned spectral peculiarities caused by circumstellar gas are also observed in spectra of selected post-AGB stars with circumstellar envelopes. The most appropriate example is a semiregular variable star QYSge identified with the IR-source IRAS 20056+1834 (Rao et al. 2002). But, in contrast to R CrB stars, typical spectral peculiarities in spectra of post-AGB stars are independent on observing moment, they are permanently visible.
3.2. The sharp emission lines

As during the earlier declines of R CrB the emission lines dominate the spectrum and most lines could be classified as sharp lines of neutral and singly ionized metals. By April 11, when the star was still by 1.5 magnitudes fainter than in maximum, the sharp emission lines have disappeared. The mean heliocentric radial velocity of these sharp lines is $v_{\text{rad}} = 21.0 \pm 0.5 \, \text{km s}^{-1}$ and mean FWHM is about $22.2 \pm 1.9 \, \text{km s}^{-1}$. Therefore we confirm Rao et al. (2006) findings that the sharp lines in 2003 are somewhat broader than in 1995-1996, when their FWHM was about $15 \, \text{km s}^{-1}$, and that the sharp emission lines were not shifted relative to the mean stellar velocity at maximum light ($+22.5 \, \text{km s}^{-1}$). During the earlier dimming in 2000 the sharp emission lines showed the blueshift around $6 \, \text{km s}^{-1}$ relative to mean systemic velocity (Kipper 2001).

Most of the sharp emission lines have red components which are shifted by about $22 \, \text{km s}^{-1}$ and the widths somewhat less than of the main (Fig. 2) components. As an example in Fig. 3 the gaussian decomposition of Ba II line at 649.691 nm is presented. The main component of this line has the heliocentric radial velocity $21.5 \, \text{km s}^{-1}$ and FWHM

![Fig. 2. The profiles of some emission lines in velocity scale. The velocity scale is set for the blue components.](image-url)
Fig. 3. The gaussian decomposition of the Ba II line at 649.691 nm. The positions of the components are indicated by the vertical lines. The sum of the gaussian components is drawn by dashed line.
20.8 km s$^{-1}$. The red component is shifted by 22.2 km s$^{-1}$ and has FWHM=12.9 km s$^{-1}$. During the 2000 light decline the sharp emission lines had inverse P Cygni profile with red absorption shifted by 42.0 $\pm$ 2.5 km s$^{-1}$ from the emission core (Kipper 2001). During the 1995 minimum these absorption components were also visible (Rao et al. 1999). Such inverse P Cygni components were not reported for the 2003 decline by Rao et al. (2006). However, their Fig. 10 shows weak absorption components at both sides of sharp emission lines.

He I is presented only by weak emission line at 587.567 nm. This line usually shows broad emission during light declines. In the February 24 spectra the line is sharp with FWHM=24.5 km s$^{-1}$ and shows red emission component similarly to other sharp lines.

In the observed spectral region C I is presented only with two emission lines at 569.313 and 667.553 nm with heliocentric velocities of 15.8 and 16.8 km s$^{-1}$. This means that the C I lines are blueward shifted about 6 km s$^{-1}$ relative to other sharp lines.

From forbidden lines only the [O I] lines at 630.031 and 557.734 nm were present on February 24 spectra. The first [O I] line is blended with Sc II line at 630.074 nm. The gaussian decomposition of that blend is depicted in Fig. 4. The heliocentric velocity of the [O I] line is 21.0 km s$^{-1}$. The Sc II line also has a red emission component shifted by 20.5 km s$^{-1}$.

We were not able to identify nonmolecular absorption lines in February 24 spectra, with possible exception of few nearly zero-excitation ($\varepsilon_i = 0.11 \div 0.12$) Fe I lines with velocities about 14 km s$^{-1}$. The identification of these lines is uncertain. In this respect the 2003 decline differs from the 2000 minimum when we found rich absorption spectrum. The strongest lines belonged to C I but the lines of Fe I, Fe II, Cr I, O I, Mg I, Na I and Si II were also present (Kipper 2001).

3.3. The broad emission lines

From the category of broad emission lines only the Na I D lines were visible in February 24, 2003 spectra (Fig. 5). As during the earlier declines the Na I doublet consists of broad and sharp emission components. Also, the sharp interstellar (IS) lines of the doublet were visible. The mean over three observing epochs heliocentric velocity of IS lines is $22.1 \pm 1.1$ km s$^{-1}$. The stated error could be considered as the possible error of all our radial velocity measurements.

The sharp emissions of Na D lines are slightly blueshifted ($\approx 3$ km s$^{-1}$) relative to other sharp emission lines and FWHM=21.4 km s$^{-1}$. The broad component of D$_2$ line extends to $-266$ km s$^{-1}$. Superimposed
Fig. 4. The gaussian decomposition of the blend of [O I] and Sc II lines at 630.05 nm. The solar wavelengths are indicated for the identified lines. The measured value is indicated for the Sc II red component.
Fig. 5. Observed spectra of R CrB near the Na I D doublet. The velocity scale is set for the D2 line. Full line – spectrum for February 24, dashed line – the one for April 11, 2003, and dotted line – spectrum in light maximum (January 12, 2004).
In the April spectra two strong blueshifted absorption components of D$_2$ line are visible at heliocentric velocities $-230$ and $-172$ km s$^{-1}$. The absorption profile in D$_1$ line is more complicated. The most blueshifted components are at the velocities of $-218$ and $-178$ km s$^{-1}$. Such high-velocity gas has also been reported for other declines of R CrB stars after minimum light (Rao et al. 2004).

The photospheric absorption of NaI consists of two components at heliocentric radial velocities 4.4 and 31.5 km s$^{-1}$ (D$_2$), and 6.5 and 29.9 km s$^{-1}$ (D$_1$). The separation of these components could be caused by sharp emission in the line core.

The H$_\alpha$ line shows weak two-peaked emission in the February spectra. This emission was blueshifted relative to the photospheric absorption. In the recovery phase the line is in absorption as it is in the light maximum (Fig. 6).
3.4. The molecular lines

Rao et al. (2006) reported that their spectra of R CrB during the late phases of the 2003 dimming show C$_2$ Swan bands (1,2), (0,2), and (1,4) in emission. Our spectra for February 24, 2003 show only the C$_2$ Swan system (0,0) band in emission (Fig. 7). The lines of this band are broadened so that the rotational structure is not visible. The other observed bands (1,2), (0,1), (0,2), and (1,3) were in absorption (Fig. 8). The absorption lines are sharp with FWHM $\approx$ 22 km s$^{-1}$. We were able to determine velocities from the rotational lines of (0,1) and (0,2) bands $16.0 \pm 1.0$ and $15.4 \pm 2.6$ km s$^{-1}$ correspondingly. Some absorption lines of CN red system (5,1) band were identified with the velocity of $15.0 \pm 2.3$ km s$^{-1}$. This means that the molecular absorption lines were blueshifted relative the systemic velocity by 7 km s$^{-1}$.
Fig. 8. The portion of the spectrum of R CrB close to the $S_2$ Swan system (0,1) band head on February 24, 2003. The emission lines of Fe II and Sc II are indicated. The rotational lines of $C_2$ are sharp and well resolved.
Table 1. Heliocentric radial velocities of various spectral lines in the spectrum of R CrB during the 2003 light decline and in maximum (January, 12 2004).

| Line                     | Feb. 24 | April 11 | Jan. 12, 2004 |
|--------------------------|---------|----------|---------------|
| Na I D IS:               |         |          |               |
| D₂                       | -23.2   | -23.6    | -21.9         |
| D₁                       | -21.2   | -21.0    | -21.9         |
| Na I D sharp emission:   |         |          |               |
| D₂                       | +19.1   |          |               |
| D₁                       | +19.6   |          |               |
| Na I D broad emission:   |         |          |               |
| Blue limit of D₂         | -266    |          |               |
| Abs. on blue wing        | -99     |          |               |
| Na I photosph. absorption: |      |          |               |
| D₂                       | +4.4    | +30.5    |               |
|                           | +31.9   |          |               |
| D₁                       | +6.5    | +33.0    |               |
|                           | +29.9   |          |               |
| Na I D blue absorption:  |         |          |               |
| D₂                       | -230    |          |               |
|                           | -172    |          |               |
| D₁                       | -218    |          |               |
|                           | -178    |          |               |
|                           | -145    |          |               |
| Sharp emissions:         |         |          |               |
| Main component           | +21.0   |          |               |
| Red component            | +43     |          |               |
| CI emission              | +16.3   |          |               |
| [O I] emission           | +21.0   |          |               |
| C₂ rot. lines absorption | +15.7   |          |               |
| CN rot. lines absorption | +15.0   |          |               |
| Fe I absorption          | +14     |          |               |

4. CONCLUSION

We have presented the spectral observations of R CrB during the 2003 minimum and compared them with earlier light declines.

The sharp emission line spectrum is clearly universal during all light drops. Usually the sharp emission lines are blueshifted by about 10 km s⁻¹. In 2003 these lines were almost not shifted. At the same
time the lines widths are larger than usually. Already the usual widths around 15 km s$^{-1}$ are much larger than if caused by thermal broadening. The small or absent blueshift together with large linewidth could indicate that the line-forming region is expanding roughly with $v_{\text{exp}} \approx 10$ km s$^{-1}$.

In 2003 the sharp lines did not show inverse P Cygni profiles which were prominent in 2000. Instead, the lines showed red emission components.

The quite universal are also the broad and blueshifted absorptions of Na I D lines developing in the recovery phase.

On the descending part of the light curve C$_2$ Swan bands were in absorption except the (0,0) band. Later, during minimum light these bands were in emission. At the maximum light the C$_2$ Swan system bands are weakly in absorption.

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