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R Coronae Borealis stars at minimum light – UW Cen

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ABSTRACT

Two high-resolution optical spectra of the R Coronae Borealis (R CrB) star UW Cen in decline are discussed. A spectrum from mid-1992 when the star had faded by 3 mag shows just a few differences with the spectrum at maximum light. The ubiquitous sharp emission lines seen in R CrB at a similar drop below maximum light are absent. In contrast, a spectrum from mid-2002 when the star was 5 mag below maximum light shows an array of sharp emission lines and a collection of broad emission lines. Comparisons are made with spectra of R CrB obtained during the deep 1995–1996 minimum. The many common features are discussed in terms of a torus-jet geometry.

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

1 INTRODUCTION

R Coronae Borealis stars (here RCBs) are H-poor supergiants that decline in brightness unpredictably and rapidly by up to 8 mag to remain at or near minimum light for several weeks to months, and even years in some cases. It is generally accepted that the declines arise from the formation of a cloud of carbon soot that obscures the stellar photosphere (O'Keefe 1939). At present, spectroscopic coverage of RCBs in decline is quite limited but common signatures seem to exist.

In decline, two kinds of emission lines dominate the optical spectrum of a RCB (Herbig 1949; Payne-Gaposchkin 1963) a rich set of sharp lines (full width at half maximum, FWHM $\sim$12 km s^{-1}), and a sparse set of broad lines (FWHM $\sim$ 300 km s^{-1}). Sharp lines first appear very early in a decline and persist through deep minima into the recovery to maximum light. Initially and for a few days, the emission lines are dominated by high-excitation transitions of abundant species (e.g. C I and O I – Rao et al. 1999). After a few days and through the minimum to recovery, the sharp lines are of low excitation with singly ionized metals being well represented. Broad lines, which are seen only when the star has faded by several magnitudes and do not have a common profile, may include the following carriers: He I triplet series, Na I D and [N II] lines, i.e. a mix of high- and low-excitation lines. Broad blueshifted absorption lines have been seen to accompany Na D, Ca II H and K, and the He I lines at 10 830 and 3889 Å, especially at and following minimum light. In deep minima, the photospheric absorption lines are 'veiled', i.e. the lines become very shallow and broad.

These spectral features may be common to all RCBs. Their discovery and definition rested largely on well-observed declines of the two brightest RCBs – R Coronae Borealis (R CrB) (Payne-Gaposchkin 1963) and RY Sgr (Alexander et al. 1972). Evidence that the features may be ubiquitous is found in the valuable contributions to the spectroscopic literature of RCBs observed through a decline by Cottrell, Lawson & Buchhorn (1990) for R CrB, Skuljan & Cottrell (1999) for S Aps and RZ Nor, and Skuljan & Cottrell (2002a) for V854 Cen. Observations of a few stars in deep declines have also shown that a RCB in such a decline has common spectroscopic features, as we indicate in Section 7. Our reference point will be the extensive coverage at high-spectral resolution of R CrB in the 1995–1996 decline (Rao et al. 1999).

In this paper, we discuss high-resolution spectra of the southern RCB UW Cen taken in mid-1992 and mid-2002 when the star was in a deep decline. We comment also on low-resolution spectra of UW Cen obtained prior to 2002 when UW Cen was in the same long decline (Skuljan & Cottrell 2002b) UW Cen with R CrB and RY Sgr is a 'majority' member of the RCB class in the terminology introduced by Lambert & Rao (1994). The effective temperature ($T_{\rm eff}$ = 7500 K) and surface gravity (log g = 1.0) of UW Cen are representative of most stars (Asplund et al. 2000).

UW Cen is one of the very few RCBs with a visible circumstellar reflection nebula (Pollacco et al. 1991). The nebula varies in appearance, possibly owing to the formation and dissipation of dust clouds affecting the illumination of the nebula (Clayton et al. 1999). At maximum light, UW Cen shows light (amplitude less than 0.2 mag in V) and radial velocity variations typical of RCBs (Lawson & Cottrell 1997).

2 OBSERVATIONS

High-resolution optical spectra were obtained in 1991, 1992 and 2002 at the Cerro Tololo Inter-American Observatory (CTIO), using the 4-m Blanco Telescope and Cassegrain Echelle Spectrometer.

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The star was at maximum light in 1991, but in decline in 1992 and 2002. The 1991 July 15 (JD 2448453) spectrum covered the spectral range 5540–6780 Å at a resolving power of 12 500. A spectrum obtained on 1992 May 22 (JD 2448764) at a resolving power of 30 000 covered the spectral region from 5480–7090 Å. The AAVSO data base of variable star observations (http://www.aavso.org/data/lcg/) shows that the star was observed in 1992 at about 12th mag, or about 3 mag below maximum light. In this decline, which began 90 d before our observation, the star faded to 15th–16th mag by about JD 2448730 before brightening slightly to 12th mag and then fading again. Maximum light was not attained until about 1 year after our observation.

Two 30-min exposures of UW Cen were obtained on 2002 June 20 (JD 2452446.54). The spectrograph was set to record the wavelength interval 4900–8250 Å in 45 orders. Spectral coverage was complete between these limits. A resolving power of 35 000 was achieved. The light curve from the AAVSO data base shows that the star went into decline in late 1998. As typical of RCBs, the decline was rapid. The star was fainter than $V \simeq 13$ from mid-1997 ($V = 9.1$ at maximum), and, in particular, at minimum light with $V \simeq 15$ or possibly fainter from early 1999 to the beginning of 2001 when it brightened gradually reaching 13th mag by early 2002. At the time of our observation, UW Cen had faded again and was at $V \simeq 14$ or about 5 mag below maximum brightness. In the following months and through the 2003 observing season, it remained very faint.

3 THE 1991 SPECTRUM OF UW CEN

The maximum-light spectrum obtained in 1991 shows a good match to the 1992 spectrum when the star was about 3 mag below maximum light. The photospheric absorption lines are broad enough not to be affected by the difference in the resolution of the spectra. Fig. 1 shows the superposition of the 1991 (full line) and 1992 (dashed line) spectra in the region of Hα. It is clear that most of the lines have similar profiles in 1991 and 1992. The 1992 spectrum was used by Asplund et al. (2000) for their abundance analysis. Analysis of the 1991 spectrum would confirm that analysis.

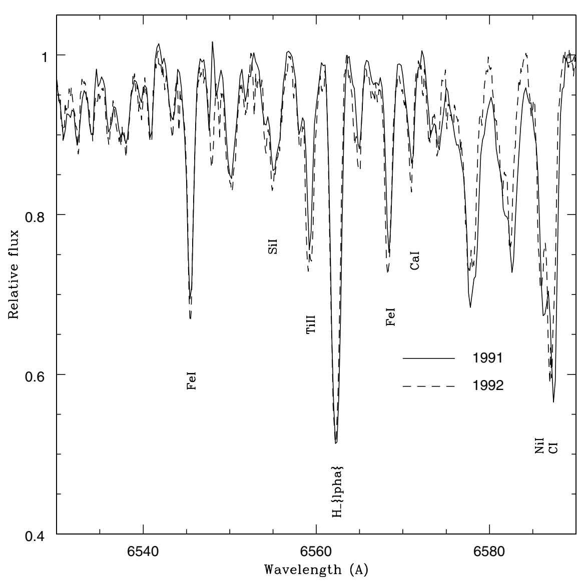

Figure 1. Comparison of UW Cen spectra obtained in 1991 (light maximum) and 1992 (light minimum). Note the good match between the lines including Hα.

The radial velocity in 1991 from 32 unblended lines across the 5800–6750 Å interval is $-31.8 \pm 2.6\,\mathrm{km\,s^{-1}}$ with two strong Ba II lines indicating a velocity of about $-20\,\mathrm{km\,s^{-1}}$. Lawson & Cottrell (1997) obtained radial velocities on 10 occasions between 1991 May and 1991 September from spectra of the 6540–6640 Å interval with a resolving power of 10 000. Their two observations close to the time of our observation give a velocity of about $-21\,\mathrm{km\,s^{-1}}$, a value differing by $12\,\mathrm{km\,s^{-1}}$ from our measurement.

4 THE 1992 SPECTRUM OF UW CEN

When observed in 1992, UW Cen was about 3 mag below maximum light yet the 1992 spectrum closely resembles the 1991 maximum-light spectrum. The prominent difference is that certain strong low-excitation lines are strengthened in the 1992 spectrum, notably strong lines of Sc II and Ba II: Fig. 2 shows the 6095–6160 Å interval where strengthening of the Ba II 6140 Å line in 1992 is conspicuous. Strengthened lines are slightly redshifted ($7\,\mathrm{km\,s^{-1}}$) relative to the photospheric velocity of $-43.8 \pm 1.5\,\mathrm{km\,s^{-1}}$, as measured from 23 lines.

It is a well-known fact that when the well-observed stars R CrB and RY Sgr decline, sharp emission lines appear in great numbers across the optical spectrum from very early in the decline until late in the recovery phase. The striking aspect of the 1992 spectrum of UW Cen is that the only sharp emission lines are at the Na D lines. Fig. 3 shows sharp emission cores in the Na D lines at a radial velocity of $-35.0\,\mathrm{km\,s^{-1}}$. This emission is redshifted by about $9\,\mathrm{km\,s^{-1}}$ with respect to the photospheric absorption lines.

Fig. 3 also shows blueshifted absorption Na D lines in the 1992 spectrum with absorption minima at heliocentric radial velocities of -157 and $-194\,\mathrm{km\,s^{-1}}$. The high-velocity Na D components are attributed to a shell ejected and accelerated earlier. In analogy with the 1995–1996 minimum of R CrB (Rao et al. 1999), it would be expected that the shells were ejected at about the time that minimum light was attained, some 60–90 d before our spectrum was taken, and accelerated to the observed velocities.

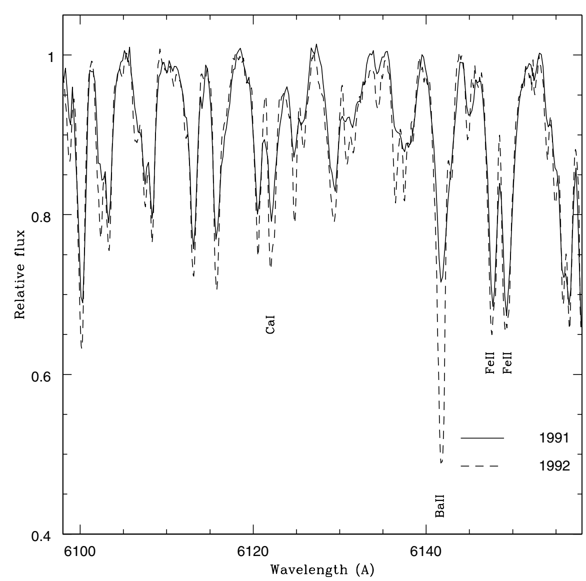

Figure 2. Comparison of spectra of UW Cen obtained in 1991 and 1992. Note the strengthening of the Ba II 6141-Å line in the 1992 spectrum.

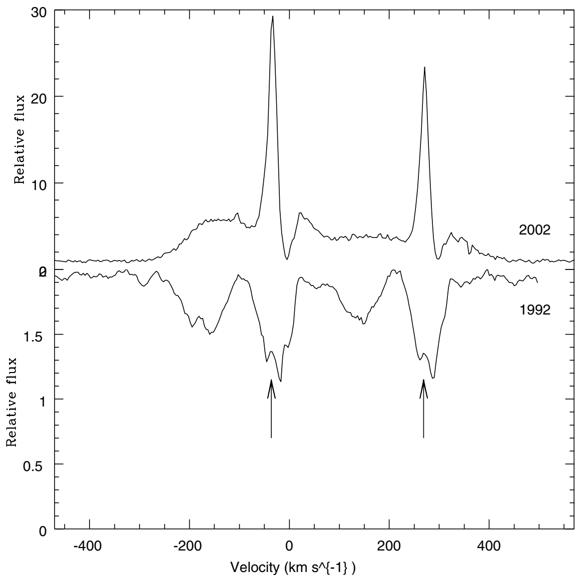

Figure 3. Comparison of UW Cen spectra around the Na I D lines for the 1992 and 2002 minima. Note the presence of sharp emission in the core of a D line in 1992 (indicated by arrows) at the same velocity as the prominent emission in the 2002 spectrum. Blueshifted shell absorption components are present in the 1992 spectrum at -157 and $-194\,\mathrm{km\,s^{-1}}$.

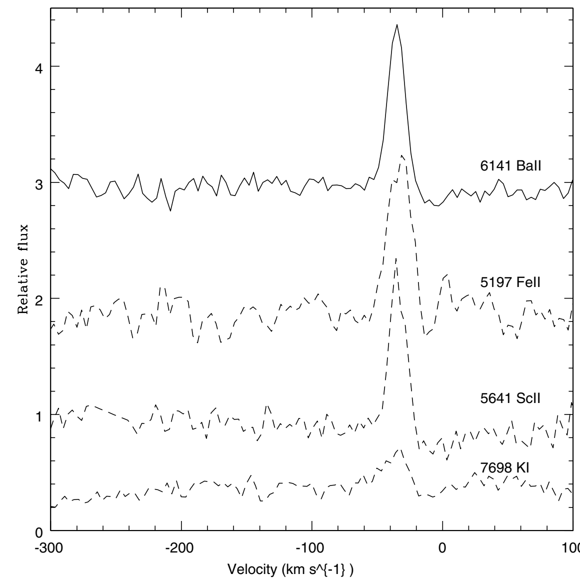

Figure 4. Profiles of sharp emission lines showing redshifted absorption. The peak radial velocity of the emission is at $-34\,\mathrm{km\,s^{-1}}$ and the weak absorption component is at about $6\,\mathrm{km\,s^{-1}}$.

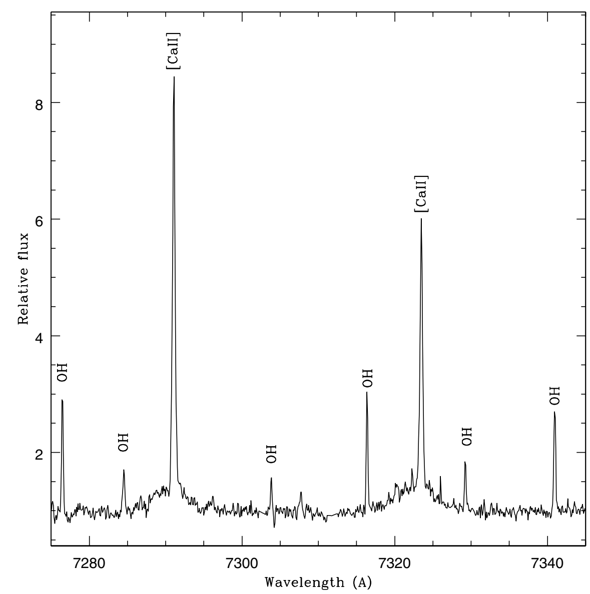

Figure 5. The [Ca II] lines in the 2002 minimum spectrum of UW Cen.

5 THE 2002 SPECTRUM OF UW CEN

The 2002 spectrum resembles that of R CrB observed at minimum light (Rao et al. 1999): sharp emission lines of singly ionized metals are prominent; broad emission lines of Na D and He I 7065 Å stand out and others are revealed by close inspection; the continuum is almost unmarked by the photospheric absorption lines prominent in the spectrum at maximum light. Detailed discussion of these components follows.

5.1 The sharp emission lines

Permitted and forbidden atomic lines are present as sharp emission lines. The list of atomic lines is dominated by low-excitation lines of singly ionized metals, e.g. Sc II (Revised Multiplet Table RMT, 19, 28, 29, 31, 26, 27), Ti II (RMT 101, 92, 91, 69, 103, 70, 86, 71), Fe II (RMT 74, 40, 48, 49, 42), Y II (RMT 26, 20) and Ba II (RMT 1, 2). Except for the Na I D lines and K I (RMT 1), sharp emission lines of neutral atoms are not present. Li I at 6707 Å, a strong absorption line at maximum light, is not present either in absorption or in emission. Molecular emissions (C_2 and CN) are not present. The sharp lines are slightly broader than the instrumental width (as assessed from the [O I] night sky emissions): the FWHM of the sharp lines, after correcting for the instrumental width is $11.4\,\mathrm{km\,s^{-1}}$. The radial velocity as determined from 53 sharp lines is $-34.6 \pm 1.9\,\mathrm{km\,s^{-1}}$. Our spectrum was not flux calibrated, but the similarity between the lines of UW Cen and R CrB suggests that the excitation temperature of the emitting region of UW Cen is similar to that derived for R CrB, i.e. $T_{\mathrm{exc}} \simeq 4000\,\mathrm{K}$.

Some strong emission lines are accompanied by redshifted absorption (see Fig. 4). The absorption appears at velocities between -4 and $-11\,\mathrm{km\,s^{-1}}$. It is unlikely that the absorption component is simply the result of emission superposed on the photospheric line. As the absorption-free unblended sharp emission lines are symmetrical about the emission peak, it is unlikely that the absorption component has eaten into the sharp emission line.

A few forbidden transitions are seen as sharp emission lines: [Ca II] at 7291 and 7323 Å, and [Fe II] at 7155 Å. The sharp [Ca II] lines are superposed on broader components (Fig. 5). The sharp forbidden components are at a velocity of $-33\,\mathrm{km\,s^{-1}}$, a value consistent with sharp permitted emissions. The line width (FWHM), after correcting for the instrumental width is about $13\,\mathrm{km\,s^{-1}}$, also consistent with other sharp emission lines.

5.2 The broad emission lines

Broad emission lines include He I at 5876 and 7065 Å, the Na D lines, and lines of [N II], [S II], and [Ca II]. The He I lines have a roughly parabolic line profile. The [N II] profiles are double peaked, but the weaker [S II] lines are single peaked.

5.2.1 He I lines

The He I lines at 5876 and 7065 Å are seen as broad emission lines with a P-Cygni profile (Fig. 6). The rest wavelengths (5875.652

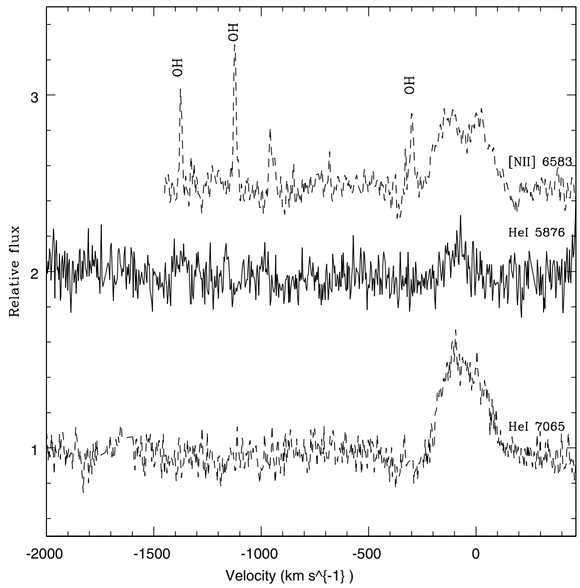

Figure 6. He I lines at 5876 and 7065 Å in the 2002 minimum spectrum. In contrast to the parabolic He I profiles, the [N II] line shows a double-peaked emission profile.

and 7065.277 Å) are taken from laboratory wavelengths with the unresolved components weighted by their theoretical intensities for optically thin emission. The 7065 Å line may have a P Cygni profile with weak absorption to $-460\,\mathrm{km\,s^{-1}}$ and maximum absorption at $-305\,\mathrm{km\,s^{-1}}$. The broad emission is centred at $-66\,\mathrm{km\,s^{-1}}$, extending on the redside to about $112\,\mathrm{km\,s^{-1}}$. It may also be noted that there is no sharp emission superposed on these broad lines.

5.2.2 *Na D lines*

The Na D lines show a broad emission profile with superposed sharp emission (Fig. 3). The blue edge of the broad emission of D2 extends to $-273\,\mathrm{km\,s^{-1}}$. The red edge of D1 extends to $+128\,\mathrm{km\,s^{-1}}$. The profile (after removing the sharp emission) can be fitted by a double-peaked profile consisting of two Gaussians, each with a FWHM of $127\,\mathrm{km\,s^{-1}}$, a separation of $144.0\,\mathrm{km\,s^{-1}}$, and of roughly equal flux. The flux ratio of the D2 to D1 broad emission lines is about 1.8, close to a ratio of 2.0 for optically thin emission lines.

5.2.3 *Forbidden lines*

[Ca II]: the Ca^{+} ion is expected to contribute broad emission lines at 3968 and 3933 Å (the H and K lines), the infrared triplet lines at 8542, 8662 and 8498 Å, and the forbidden lines at 7291 and 7323 Å. Our spectrum does not cover the wavelength regions of the permitted lines. The broad component of the forbidden lines is of approximately the same strength for the two lines (Fig. 5). The velocity range at the base of the broad emission extends from about -250 to $+103\,\mathrm{km\,s^{-1}}$ with a centre at about $-61\,\mathrm{km\,s^{-1}}$, and FWHM of about $222\,\mathrm{km\,s^{-1}}$.

[N II]: the 6583 and 6548 Å lines are present as broad emissions. The 5754 Å line is not detected. Fig. 7 shows the 6583 Å [N II] line as double peaked. Rest wavelengths of 6583.454 and 6548.08 Å have been adopted (Dopita et al. 1997). The velocity range at the base extends from -245 to $+135\,\mathrm{km\,s^{-1}}$. The red and blue peak are separated by $145\,\mathrm{km\,s^{-1}}$ with the blue peak at $-128\,\mathrm{km\,s^{-1}}$ and the red peak at $+17\,\mathrm{km\,s^{-1}}$ for the 6583 Å line, the stronger line of

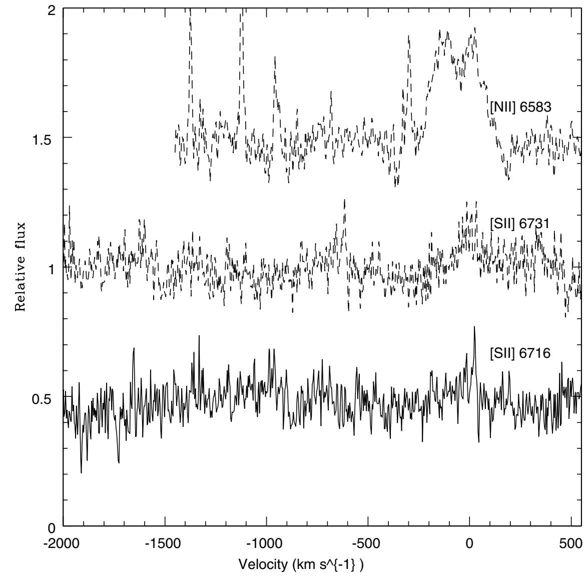

Figure 7. Lines of [N II] and [S II] in the spectrum of the 2002 minimum of UW Cen.

the pair. The peaks are about equal strength, and of similar width (FWHM of $120\,\mathrm{km\,s^{-1}}$). The mean velocity is about $-56\,\mathrm{km\,s^{-1}}$.

[S II]: the red lines at 6717 and 6731 Å are present in emission. Rest wavelengths are adopted from Dopita et al. (1997), namely, 6716.472 and 6730.841 Å. The [S II] line profiles differ in a surprising way from the profiles of the [N II] lines: both [S II] lines show the red but not the blue peak of the [N II] profiles (Fig. 7). The red peaks of the [S II] and [NII] lines have approximately the same width. The equivalent width of the 6731 Å line is about twice that of the 6717 Å line. This ratio for gas at a temperature of about 10 000 K (or less) corresponds to an electron density of $n_e \simeq 10^{3.7}\,\mathrm{cm^{-3}}$ (Aller 1984).

5.3 Absorption lines

The normal photospheric spectrum is absent. Fig. 8 shows the region of the strong photospheric line of Si II at 6347 Å from the 2002

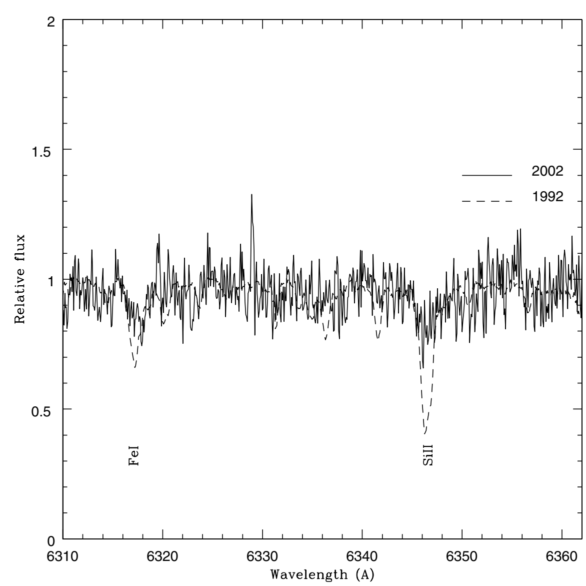

Figure 8. Absorption lines in spectra of UW Cen at the 2002 and 1992 minima. Note the shallow Si II 6347 Å line in the 2002 minimum spectrum.

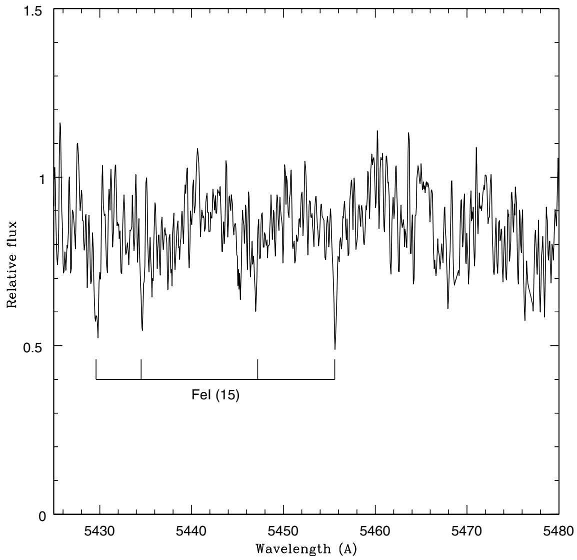

Figure 9. Low-excitation Fe I transitions in the 2002 minimum spectrum showing a sharp absorption line unaccompanied by emission.

and 1992 spectra. Clearly, photospheric lines are 'veiled' in the 2002 spectrum. The radial velocity estimated from some 15 lines is $-4.3 \pm 5.7\,\mathrm{km\,s^{-1}}$ where the large standard deviation reflects the difficulty of measuring these weak broad lines.

A few narrow absorption lines do appear in the 2002 spectrum but these are not photospheric lines. Fig. 9 shows several low-excitation lines of Fe I in absorption without any accompanying emission. They provide a radial velocity of $-9.7 \pm 4.3\,\mathrm{km\,s^{-1}}$ from six lines, a velocity similar to that of the redshifted absorption components associated with the sharp emission lines.

6 UW CEN AND R CRB IN DECLINE

The components of the spectrum of UW Cen in the 2002 deep minimum are similar to those seen during the 1995–96 minimum of R CrB (Rao et al. 1999). These components include the veiled photospheric spectrum, low-excitation sharp emission lines, broad emission lines and high-velocity blueshifted absorption lines seen in the Na D lines. Other minima of R CrB show the same components, as do the limited observations of other R CrB stars in decline. In this section, we compare spectroscopic properties of UW Cen and R CrB at minimum light.

6.1 Sharp emission lines

Sharp high-excitation emission lines were seen in R CrB for a short period beginning just after the onset of the decline. As our UW Cen spectrum was taken long after the onset of the decline it is not suprising that the equivalent lines are absent.

Lower excitation lines of singly ionized metals and neutral atoms are seen in R CrB following the disappearance of the high-excitation lines. These lines show a similar level of excitation for the two stars. The line widths are also similar for the two stars. The sharp emissions made their initial appearance in the cores of the absorption lines of R CrB when the star had faded by about 3 mag. At the time of our 1992 observation, when UW Cen was about 2.7 mag fainter than at maximum, sharp emission lines are detected only in the Na D line cores, suggesting that the emitting region was weaker or more obscured than in the case of R CrB. Sharp emission lines are prominent in the 2002 spectrum when UW Cen was about 5 mag below maximum light.

That the sharp Na D line emission for UW Cen occurs at the same velocity ($-35\,\mathrm{km\,s^{-1}}$) in 1992 and 2002 minimum suggests that the emitting gas may be a semipermanent feature detached from the stellar photosphere. This is consistent with observations of R CrB showing a constant velocity for sharp emission lines and a variable velocity for photospheric lines.

Redshifted absorption associated with sharp emission lines is seen in UW Cen and was seen in the early stages of the R CrB decline, and also in a decline of V854 Cen (Rao & Lambert 2000). The 2002 spectrum of UW Cen also shows this absorption component in low-excitation Fe I lines without any accompanying emission. Comparison of the 1991 maximum and 1992 minimum spectra shows strong absorption lines of Ba II redshifted relative to other absorption lines. The redshifted absorption suggests that cool gas is falling toward the star – perhaps from the detached region responsible for the sharp emission lines.

6.2 Broad emission lines

The inventory of broad emission lines in UW Cen in 2002 does not precisely duplicate that for R CrB at its minimum across the common wavelength interval. The profile of a line in UW Cen and the same line in R CrB are generally similar, most notably the He I lines have a quasi-parabolic profile, and the [N II] lines are double peaked. The [S II] lines are seen in UW Cen [also, V854 Cen, Rao & Lambert (1993)] but not in R CrB. The K I 7664 and 7699 Å lines were seen in R CrB but not in UW Cen. The C_2 Swan bands were in emission in R CrB but not in UW Cen. These differences may reflect differences in composition and physical conditions rather than major structural differences.

The low-excitation sharp emission lines in R CrB, UW Cen and all other stars where they have been seen, occur with a small blueshift relative to the photosphere. Broad emission lines share neither the velocity of the sharp lines nor the velocity of the photosphere, and appear not to be constant for a given star. For UW Cen in 2002, the broad emissions are displaced to the blue by $26\,\mathrm{km\,s^{-1}}$ from the sharp emission lines (the mean broad-line velocity is $-61\,\mathrm{km\,s^{-1}}$). This mean velocity is outside the range of reported photospheric velocities: -10.1 to $-26.8\,\mathrm{km\,s^{-1}}$ (Lawson & Cottrell 1997), $-29.3\,\mathrm{km\,s^{-1}}$ (Herbig, private communication) and $-43.8\,\mathrm{km\,s^{-1}}$ (this paper). In the case of R CrB in the 1995–1996 minimum, the broad lines were blueshifted by about $20\,\mathrm{km\,s^{-1}}$. For RY Sgr in separate declines Alexander et al. (1972) and Spite & Spite (1979) reported differing redshifts of the broad lines relative to the sharp lines, but Asplund (1995) found broad and sharp lines at the same velocity. An especially intriguing star is S Aps where the broad Na D lines were blueshifted by about $100\,\mathrm{km\,s^{-1}}$ relative to the sharp emission lines with their normal small blueshift with respect to the photosphere (Goswami et al. 1997).

6.3 Blueshifted Na D absorption

Observations of R CrB in the 1995–1996 minimum showed the blueshifted high-velocity Na D absorption developing in strength and velocity shortly after minimum light. Such high-velocity gas has been reported for other declines of R CrB and other R CrB stars. It is then not surprising that the 1992 spectrum of UW Cen obtained about 2 months after the star had reached minimum light should show high-velocity absorption in the Na D lines.

High-velocity absorption with a profile like that of the 1992 components is not present in our 2002 spectrum. Very broad shallow absorption could be difficult to impossible to detect given the presence of the broad emission line. Absorption at velocities less than about $-250\,\mathrm{km\,s^{-1}}$ is definitely absent.

Observations of the Na D lines are reported by Skuljan & Cottrell (2002b) who observed UW Cen at low resolution ($\Delta\lambda \simeq 3$–6 Å) during a partial recovery to $V \simeq 13$–14 in the deep extended decline in which our 2002 spectrum was obtained. These Na D observations were obtained between 534 and 622 d from the onset of the decline, and about 4 years before our observation. The spectra appear to show blueshifted absorption at a velocity of about -220 to $-300\,\mathrm{km\,s^{-1}}$. Such a component is not present in our spectrum. (Skuljan & Cottrell did not detect broad Na D emission lines but remark that 'they are probably at or below the noise level in the continuum'.)

7 DUSTY TORUS AND BIPOLAR JETS

In line with contemporary fashion for models of mass-losing luminous low-mass stars (Lopez 1999; Rao, Goswami & Lambert 2002) including RCB stars (Rao & Lambert 1993; Clayton et al. 1997), we invoke the geometrical combination of bipolar jets and an equatorial torus of dust and gas.

There are observational hints that there is a preferred plane (i.e. a torus) for dust formation and ejection (Clayton et al. 1997; Rao & Raveendran 1993). Observational evidence, especially measurements of the infrared flux emitted by the circumstellar dust, suggests that the dusty region is comprised of clouds (Feast 1986; Feast et al. 1997) and a decline results when a new cloud forms along the line of sight. If dust formation is restricted to a preferred (equatorial) plane and clouds confined to a torus, dust-forming RCB stars observed at high inclination to the torus will not exhibit declines but will possess an infrared excess. The stars Y Mus and XX Cam may be such examples (Walker 1986; Clayton 1996). At the other extreme, there may be stars with the torus perpendicular to the plane of the sky and, if the torus is optically thick, these RCBs will be difficult to identify.

We speculate how a torus-jet model may account for the spectroscopic signatures of an RCB in decline, including the sharp emission lines, the broad emission lines, the veiled photospheric lines and the high-velocity blueshifted Na D absorption as follows.

(i) Sharp low-excitation emission lines, we suppose, originate from the base of the jets where the jet velocity is low. Depending on the geometry of the jet and torus, the viewing angle and the size of the new cloud, the base of the jet on the far side may be obscured. In which case, the sharp lines will always have a net blueshift determined by the jet outflow velocity near its base, the angle of inclination and the volume of the emitting region unobscured by dust. The characteristic velocity of the lines when the star is in decline is $-10\,\mathrm{km\,s^{-1}}$ relative to the photosphere.

(ii) Double-peaked broad emission lines (e.g. [N II] but not He I) are identified with regions of the jets quite distant from the star and visible to us along paths not intersecting the newly formed cloud and the dusty torus. The double-peaked profiles have a ready explanation: the blueshifted peak comes from the jet nearer to us and the redshifted peak from the opposing jet. The details of the profile depend on the jet velocity and the opening angle and the angle of inclination to the line of sight. The mean velocity could be, as observed for UW Cen, blueshifted relative to the photospheric velocity if the receding jet is partly obscured by the dusty torus. However, this construction would likely predict unequal fluxes in the blue and red halves of the line, which is not the case (see also Rao et al. 1999, for R CrB).

If there is a steep transition from subsonic to supersonic flow (i.e. a Parker-type wind), lines with profiles intermediate between the sharp and broad lines will be absent, as observed. This geometry is consistent with the observation of Whitney et al. (1992) that the Na D broad lines from V854 Cen are unpolarized even though the local continuum is significantly polarized. It is also consistent with the indication that the broad-line flux is probably constant through a decline, as shown by Skuljan & Cottrell (2002a) for V854 Cen, and by Rao et al. (1999) for R CrB.

(iii) Judged by differences in profile and derived physical conditions, the He I lines cannot be produced by the gas responsible for the [N II] and similar lines. The He I emission is here identified with the dusty equatorial torus. Gas in the clouds causing a decline is accelerated quite quickly to high velocities, as revealed by the blueshifted Na D absorption. Dust ejection is known to occur in localized regions. Then, the torus will be populated by many high-velocity clouds. Collisions in the torus between the high-velocity atoms in a high-velocity dust cloud and slowly moving older residents (electrons, He atoms and dust grains) of the torus, may provide sufficient excitation to cause emission. As the He I emission may come from regions spread across the torus, expansion (or rotation) of the torus will provide a roughly parabolic emission line profile provided that the number of contributing clouds is not small. A velocity shift from the photospheric velocity will occur if the clouds are asymmetrically around the torus.

Evidence for excited He atoms along the line of sight to RCB stars is provided by the observations of Clayton et al. (2003) of the He I 10 830 Å line in a sample of RCB stars. In stars observed near maximum light, the 10 830 Å line (with the exception of V854 Cen) is strongly in absorption with a blueshift of 200–300 $\mathrm{km\,s^{-1}}$. There is a hint of P Cygni emission with a suggestion that the emission is stronger for stars observed in decline. Although a detailed study of He I excitation is needed, these observations are consistent with our speculation about the origin of the the 7065 Å and other lines, all of which must be much weaker than the 10 830 Å line.

(iv) When the star is thoroughly obscured by the dust cloud responsible for the decline, it is seen by starlight scattered multiple times by dust in the torus. These dusty clouds expanding outward will impose a range of Doppler shifts on the scattered starlight. The result is a greatly smeared (veiled) version of the photospheric spectrum is received by the observer.

(v) In the recovery phase, the sightline to the star is becoming less opaque. Gas along this sightline may be seen in absorption against the reduced photospheric continuum, seen through the new cloud and also be scattering off other dust clouds. Some of this gas is associated with the dust which caused the decline and some may be in the expanding torus as a result of earlier declines. Dust is accelerated by radiation pressure and gas–dust collisions transfer momentum to the gas. This outward moving gas provides the blueshifted absorption lines in the Na D and other resonance lines of abundant atoms and singly charged ions (e.g. Ca^{+}). In a very deep decline, the starlight is scattered into the line of sight from dust primarily off the line of sight to the star. The absence of Na D absorption at this time implies that the high-velocity gas is confined to a plane and is not spherically distributed about the star.

This sketch of the torus-jet model does not address why a RCB star should have a preferred plane for formation and ejection of dust and a pair of polar jets. The key to the preferred plane may possibly be linked to the origin of a RCB star. A favoured model involves the accretion of a He white dwarf by a C–O white dwarf. Accretion may lead to heating and swelling of the merged envelope, i.e. to the observed supergiant. One might suppose that C–O white dwarf is greatly spun up during accretion and, therefore, the RCB retains a memory of the binary orbital plane. Origins of the bipolar jets and the formation of dust clouds in the equatorial plane are left for a future theoretical study.

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