THE SPECTRUM OF THE COOL R CORONAE BOREALIS VARIABLE Z URSAE MINORIS AT MINIMUM

by Aruna Goswami, N. Kameswara Rao
Indian Institute of Astrophysics, Bangalore
and David L. Lambert
Department of Astronomy, University of Texas at Austin

We present a high-resolution spectrum (4840–10250Å) of the cool R Coronae Borealis variable Z Ursae Minoris (Z UMi) in its 1997 decline. In addition to the photospheric absorption lines, the spectrum exhibits narrow emission lines of Na I, Ti I, Fe I, and Ba II. Broad emission lines of He I and Na I *D*, which are generally seen in warmer RCBs in decline, are not noticed in Z UMi's decline spectra at this phase. This lack is the principal novel feature of the Z UMi spectrum.

Introduction

RCB stars are a rare class of which very few have been studied spectroscopically in their characteristic deep declines. This is particularly true of cool RCB stars. Indeed, only one cool RCB star, S Apodis[1], in decline has been investigated at high spectral resolution. The present study discusses high-resolution spectra of a second cool RCB star, Z UMi, in its decline and contrasts it with that of S Aps. Z UMi was suggested to be an RCB star by Benson *et al.*[2] in part on the basis of their photometric observations, which recorded a rapid decline in optical brightness of about 6 mag — a characteristic of RCB variables. Another characteristic of RCB stars is that they are hydrogen deficient.

From an analysis of high-resolution spectra taken at maximum light, Goswami *et al.*[3] showed that the star is hydrogen deficient and thus confirmed it to be an RCB variable. (The star had been earlier listed as a long-period Mira variable[4,5].) Studies by Jura *et al.*[5] show that the star has an infrared excess: the *V*–[12] colour is similar to that of other RCB stars[6]. An RCB star's decline is attributed to the formation of clouds of carbon soot. A goal of studies of spectra of RCBs in decline is to define the nature of the regions producing emission lines and their relation to the obscuring dust clouds.

Spectroscopic monitoring of warm RCBs such as R CrB and RY Sgr (see Clayton's review[7]) shows that the initial phases of a decline are marked by the appearance of sharp emission lines from (mostly) singly-charged ions, with a progressive lowering in level of excitation as the decline progresses. There is evidence that the sharp emission lines are a permanent feature providing an emission core to strong absorption lines at maximum light. A few broad lines, noticeably the Na *D* lines and He I lines, appear when the star has faded by about 4 magnitudes from maximum light.

Observations and data reduction

High-resolution spectra of Z UMi were obtained using the 107-inch *Harlan J. Smith* telescope at the McDonald Observatory on 1997 June 22 and 23. The

TABLE I

Prominent emission lines seen in the decline spectrum of Z UMi

Wavelength[15] *(Å)*	*Identification*	V_r *km s*$^{-1}$	*Equivalent width (mÅ)*	*FWHM km s*$^{-1}$
5889·953	Na I	−33	157	22
5895·923	Na I	−33	159	22
6364·929	Ti I	−33	8	6
5269·541	Fe I	−35	15	15
5328·042	Fe I	−35	10	15
5397·131	Fe I	−37	15	16
5405·778	Fe I	−38	38	7
5455·613	Fe I	−36	9	7
6353·849	Fe I	−30	14	14
4942·495	Cr I	−39	5	7
4934·086	Ba II	−35	24	19
6496·896	Ba II	−37	25	16
5455·140	La I	−37	13	13

2dcoudé spectrograph[8] provided a wavelength coverage of 4800–10 000Å from four exposures, two of 60 minutes on each night, at a spectral resolving power of about 30 000. A Th+Ar hollow-cathode-lamp exposure was used for wavelength calibration. The CCD data were reduced using the IRAF software package. The two exposures from the same night were combined to increase the signal-to-noise ratio. The final S/N ratio attains a maximum of about 45 in the continuum at about 7000Å. Due to contamination from moonlight, strong lines from the solar spectrum appear in the blue and thus our spectra are not useful below about 4800Å.

The spectrum

Our spectrum of Z UMi appears to represent the onset of a decline when a narrow emission-line spectrum is generally seen. At the time of observation, Z UMi was at a magnitude of about 13 according to our visual estimate. At maximum light Z UMi is near a visual magnitude of 10·8, and about magnitude 16·7 at its dimmest[2].

Although the narrow emission-line spectrum is believed to be a common and permanent feature of RCB stars, the emission lines remain unseen until the brighter photospheric spectrum gets obscured by clouds of carbon soot. In general, the emission lines are blue-shifted by a few kilometres per second relative to the photospheric absorption lines. Table I lists the emission lines that are clearly present in the Z UMi spectrum. The Ba II 6497Å line is illustrated in Fig. 1 and the Na *D* lines are shown in Fig. 2. There are undoubtedly additional weak emission lines present whose detection is hampered by the fact that Z UMi's photospheric spectrum is rich in lines. Indeed, examination of the spectrum in decline shows a filling-in of resonance and low-excitation lines. For example, the K I 7699Å line seems to be present as a sharp depression in a sea of adjacent CN lines at maximum light but not in decline.

The radial velocity of the emission lines is given in Table I. The accuracy of the measurements is about 1 km s^{-1}, as estimated from the accurately known wavelengths of the OH night-sky lines[9] . The mean velocity is −35 ± 2 km s^{-1} which is not significantly different from the photospheric velocity of −37 ± 2 km s^{-1} reported by Goswami *et al.*[3]. Although it appears that Z UMi's

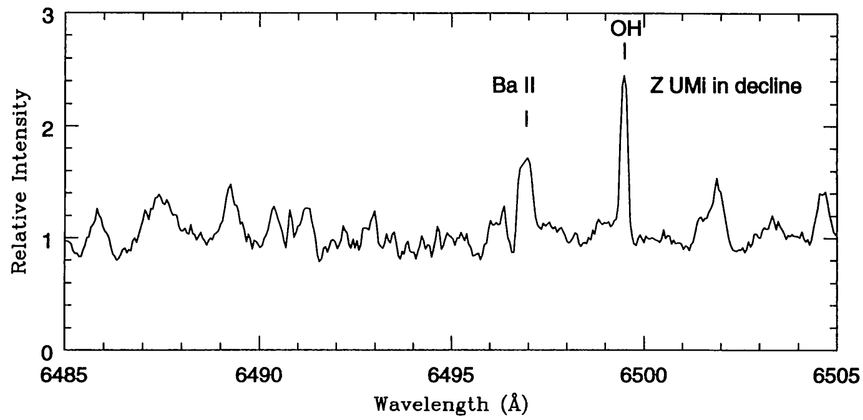

Fig. 1

The spectrum of Z UMi near 6495Å showing the sharp emission line of Ba II. Other undulations in the spectrum are gaps between deep photospheric absorption lines.

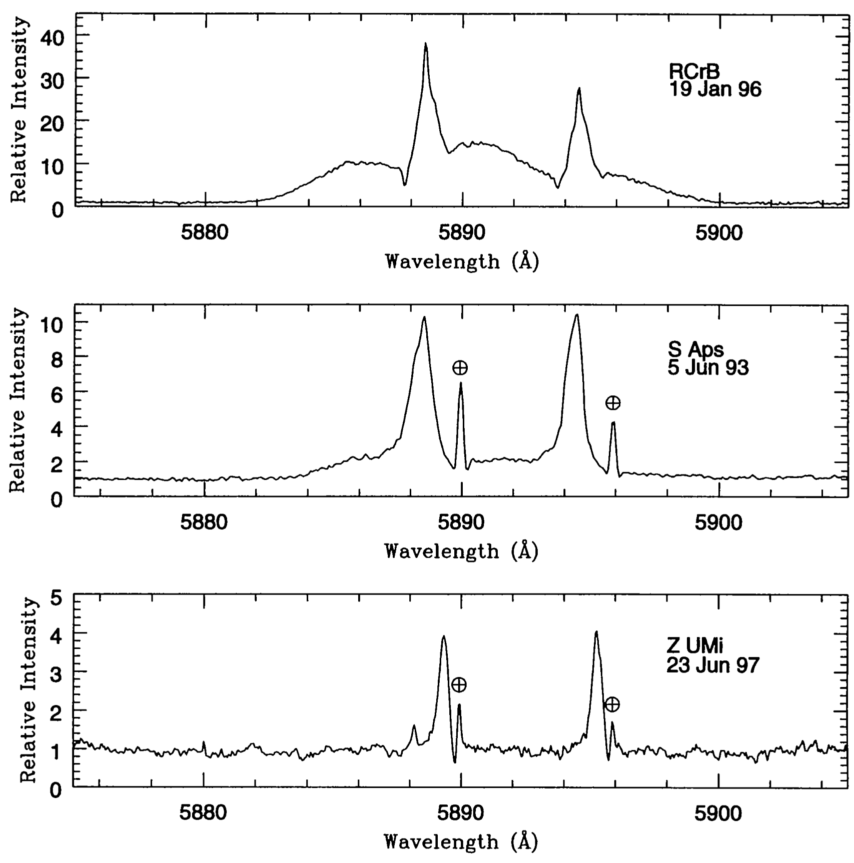

Fig. 2

The Na *D* emission feature in Z UMi (lower panel), in S Aps (middle panel) and in R CrB (upper panel). The marked telluric Na emission lines in the Z UMi and S Aps spectra are at their rest wavelengths.

sharp emission lines are not subject to the characteristic blue-shift of about 5–10 km s^{-1} reported for RCBs in decline we note that the photospheric velocity is possibly variable such that Goswami *et al.*'s measurement is not the systemic velocity. We have also tabulated in Table I the width (FWHM in km s^{-1}) of the emission lines, after correcting for the instrumental width. Emission lines of Fe I at 5405·778Å and Cr I at 4942·495Å are so narrow that they are comparable to the instrumental width.

Unlike all other RCBs observed in decline to date, Z UMi's spectrum does not exhibit broad Na *D* lines. These lines are not the only broad lines previously reported but are the strongest and most readily detected. Broad Na *D* lines have been detected in RCrB[10,11,12], V854 Cen[13], RY Sgr[14], and S Aps[1]. The broad lines of R CrB and S Aps together with our spectrum of Z UMi are shown in Fig. 2 where the absence of broad lines in Z UMi is quite evident. The spectrum of R CrB at a resolving power of 60 000 is also from the *2dcoudé* spectrograph. The spectrum of S Aps at a resolution of about 30 000 was discussed earlier[1]. Note that the Na *D* lines in all three cases include a sharp component. This component for Z UMi is narrower than for S Aps. S Aps was observed in decline about 4 magnitudes below maximum light. In the 1995–1996 deep decline of R CrB, broad Na *D* emission was first obvious when the star had faded by 2·5 magnitudes (paper in preparation). Our spectra of Z UMi were taken when the star was no more than 2 magnitudes below maximum light. Thus, the difference between Z UMi and S Aps may be due to the different depths of the decline at the time of observation.

From the observational evidence of R CrB and RY Sgr in decline, the only two stars for which extensive and simultaneous photometric and spectroscopic coverage in decline are available, it is evident that as the photospheric light decreases with the formation of dust clouds, a rich narrow-line (~ 50 km s^{-1}) emission spectrum comprising lines mostly due to neutral and singly-ionized metals appears. This spectrum, which is short lived, fades within two or three weeks and is replaced by a simpler broad-line (100–200 km s^{-1}) spectrum, although some of the early-decline emission lines, primarily multiplets of Sc II and Ti II, remain strong for an extended period of time. The broad-line spectrum is a late-decline appearance dominated by Na I *D* lines together with Ca II *H* and *K* and He I 3888Å, which remains visible until the star returns to within about 3 magnitudes of maximum light.

Other broad emission lines are seen in spectra of RCBs recorded in decline. In particular, broad He I lines appear; the He I line at 7065Å was strong in S Aps[1]. Although the photospheric spectrum of Z UMi is complex, it is clear that the central intensity of the broad emission line at 7065Å cannot exceed 20–30% of the local continuum intensity. He I lines at 5876 and 6678Å seen in other RCBs in decline are similarly not detected in Z UMi. Various forbidden lines of [N II] and [O II] seen, for example, in V854 Cen and/or R CrB in decline are not observed in Z UMi's spectrum.

The spectrum of Z UMi at maximum light is dominated by C_2 Swan bands. In R CrB and V854 Cen at deep declines, the C_2 Swan bands are in emission. Moreover, the individual C_2 features are much broader than their photospheric counterparts at maximum light; the C_2 bands seem to belong to the set of broad lines. In the case of Z UMi in decline, the C_2 lines remain in absorption. Fig. 3 compares the C_2 Swan 2–4 bandhead at maximum and in decline. The two spectra have been normalized to the same 'high' points beyond the bandhead, a region also containing C_2 lines. It is obvious that the depth of the bandhead

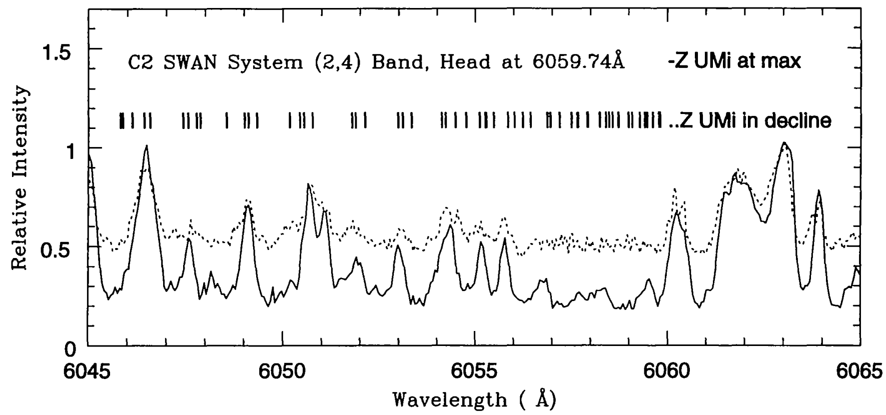

Fig. 3

The spectrum of Z UMi near the C_2 Swan 2–4 bandhead at maximum light and in decline. Note that the stellar lines are deeper at maximum light than in decline.

and the adjacent regions is less in the decline than in the maximum spectrum. This change is, however, common across the spectrum and is not solely a feature of regions rich in C_2 lines. There appear to be two simple ways in which to account for the change. First, if the temperature profile of the photosphere were shallower when faint, the contrast between the local continuum and the cores of strong features would be lessened, as observed. Second, the photospheric spectrum nearer minimum may be diluted or 'veiled' with respect to that at maximum. The veiling is equivalent to an additional flux of about 70% of the maximum flux at wavelengths defining the local continuum. Quite possibly, the veiling is a quasi-continuous spectrum. Reports of veiling extend back to Payne-Gaposchkin's study of R CrB[11]. A dramatic example of veiling was seen in V854 Cen where the observed continuum was completely continuous, *i.e.*, there was no sign of even the strongest of the absorption lines seen at maximum light[13]. In this case, it was suggested that light from the obscured photosphere percolated out by multiple scatterings in a rotating and/or expanding dusty envelope. Scatterings with consequent Doppler shifting of photons lead to a smearing of photospheric lines in the emergent spectrum. A similar but less complete process may account for our observation of Z UMi.

Concluding remarks

Our spectra are the first of Z UMi taken on the approach to minimum, and the second for any cool RCB star in decline. The most striking aspect of our spectrum is the absence of broad emission lines, notably the Na *D* lines. Emission is detected in the Na *D* lines but as sharp rather than broad lines: they are narrower than their counterpart sharp lines in S Aps. Z UMi's spectrum was obtained at an initial stage of a decline, while the spectrum of S Aps studied by Goswami *et al.*[1] corresponded to a magnitude drop of ~ 4 magnitudes. Secrets of the cool RCBs are unlikely to be revealed until spectra are obtained from maximum light into decline and the sequence of observations is continued until the return to maximum light. In particular, spectra of Z UMi in a deeper decline are needed in order to check on the presence or absence of the broad emission lines.

Acknowledgements

Aruna Goswami acknowledges the Council of Scientific and Industrial Research, New Delhi, for financial assistance. This research has been supported in part by the U.S. National Science Foundation (grant AST9618414).

References

(1) A. Goswami *et al.*, *PASP*, **109**, 270, 1997.
(2) P. J. Benson *et al.*, *AJ*, **108**, 247, 1994
(3) A. Goswami, N.K. Rao & D.L. Lambert, *PASP*, **109**, 796, 1997.
(4) P. N. Kholopov *et al.*, *General Catalogue of Variable Stars*, 4th edn. (Moscow Pub. House, Moscow), 1990.
(5) M. Jura, A. Yamamoto & S. G. Kleinmann, *ApJ*, **413**, 298, 1993.
(6) H. J. Walker, in K. Hunger, D. Schönberner & N. K. Rao (eds.) *Hydrogen Deficient Stars and Related Objects* (Reidel, Dordrecht), p407, 1986.
(7) G. C. Clayton, *PASP*, **108**, 225, 1996.
(8) R. G. Tull *et al.*, *PASP*, **107**, 251, 1995.
(9) D. E. Osterbrock *et al.*, *PASP*, **108**, 277, 1996
(10) G. H. Herbig, *ApJ*, **110**, 143, 1949.
(11) C. Payne-Gaposchkin, *ApJ*, **138**, 320, 1963.
(12) P. L. Cottrell, W. A. Lawson & M. Buchhorn, *MNRAS*, **244**, 149, 1990.
(13) N. K. Rao & D. L. Lambert, *AJ*, **105**, 1915, 1993.
(14) J. B. Alexander *et al.*, *MNRAS*, **158**, 305, 1972.
(15) C. E. Moore, *A Multiplet Table of Astrophysical Interest*, Revised Version, NSRDS-NBS 40, (NBS, Washngton), 1972

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 144: HR 5 B

By R. F. Griffin
Cambridge Observatories

HR 5 is a well-known visual binary which has made just over two revolutions since its discovery by Sir William Herschel in 1782. The components appear to be a pair of G-type dwarfs differing in brightness by about one magnitude. Photographic astrometry, as distinct from filar-micrometer measures, has indicated that the primary star is less massive than the secondary, thereby suggesting that the latter is itself multiple. Some years ago the system was reported to show photometric variations with a period of 1·08 days, and recently a circular orbit with a period of 1·026 days was derived for the secondary star from radial-velocity measurements of the system, observed from Arizona as a single star. Here, although the visual secondary is indeed confirmed to be a spectroscopic binary, its orbit is shown conclusively to have a period of 47·7 days and an eccentricity of about 0·6; the unseen spectroscopic companion is probably an early-M dwarf.