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The Spectrum of the Cool R Coronae Borealis Variable S Apodis in a Deep Decline

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ABSTRACT. A high-resolution spectrum (5575–8875 Å) of the cool R Coronae Borealis variable S Apodis in its 1993 deep decline is discussed. Narrow or chromospheric emission lines of Na I, K I, Ca II, and Ba II and broad emission lines of He I 7065 Å and Na I D are seen, as expected from published reports of warmer RCBs in decline. The surprise of the S Aps spectrum is the considerable blue shift of the broad emission component to the Na D lines. The blue shift may result from lines formed in a bipolar flow which is obscured asymmetrically by soot clouds along the line of sight.

1. INTRODUCTION

The R Coronae Borealis (RCB) variables are surely among the most enigmatic of variable stars (see Clayton 1996 for a review). Two principal characteristics define the RCBs. First, the spectra of these supergiants show weak or absent Balmer lines indicating that hydrogen is greatly underabundant. Second, the stars fade at irregular intervals. Since each of these defining characteristics lacks a full explanation at present, the label "enigmatic" seems appropriate. To remove the label will surely require additional observations. This paper concerns an observation that may provide understanding of the stars' odd variability.

For more than 50 years, the variability has been ascribed to formation of a cloud of carbon soot that obscures the visible photosphere (Loreta 1934; O'Keefe 1939). Although this idea has gone uncontested, a key question remains unanswered: where does the soot condense that comprises the obscuring cloud? One school of thought supposes condensation to occur far from the star: if condensation occurs at a radial distance R_c from the center of the star, $R_c \simeq 20R_*$ is considered "far." An opposing school argues that condensation occurs much closer to the star: $R_c \simeq 4R_*$. Clayton (1996) reviews the observational and theoretical evidence selected to make the cases for "far" and "near" condensation.

Quite obviously, condensation occurs above photosphere. Physical conditions at high altitude above the warm photosphere may be determinable from ultraviolet spectra betraying "chromospheric" emission lines. Alternatively spectra of RCBs in decline may shed light on conditions in and above the obscuring dust clouds and on the location of the clouds. Few spectra of RCBs in decline have been presented in the literature: the most notable are the seminal studies of RY Sgr by Alexander et al. (1972) and of RCrB by Herbig (1949), Payne-Gaposchkin (1963), and Cottrell et al. (1990). A spectrum of V854 Cen (Rao and Lambert 1993) obtained in a deep decline showed several features not anticipated by the earlier studies of other RCBs. In view of the apparent diversity of the RCBs with respect to their spectra in deep declines, we availed ourselves of an opportunity to capture a spectrum of an additional RCB in decline. Our spectrum of S Apodis is the first high-resolution spectrum of a cool RCB in a deep decline. The only other description of the spectrum of a cool RCB star in deep decline is that of U Aqr by Bond et al. (1979), who detected the presence of He I 3889 Å in emission in a low-resolution spectral scan.

2. OBSERVATIONS

A spectrum of the cool RCB S Aps was obtained on 1993 June 5 when the star was in a deep decline. AAVSO reports indicate a visual magnitude of 15.0 for this star which at maximum light is near a magnitude of 9.8. The decline had begun about 66 days before the observation and continued for about another 300 days with full recovery to maximum light taking about another 200 days.

The spectrum was obtained at the Cerro Tololo Inter-American Observatory with the 4-m reflector and its Cassegrain echelle spectrograph. Two exposures, each of 60 min, were recorded on a CCD and provide essentially complete spectral coverage from 5575–8875 Å at a resolving power of about 30,000.

The CCD data were reduced using an IRAF software package. The two spectra each of 60-min duration were combined to increase the signal-to-noise ratio. Th+Ar hollow cathode lamp exposures taken immediately before and after the stellar exposures were used for wavelength calibration.

These spectra are contaminated with the spectrum of scattered moonlight. A contribution from the stellar photospheric spectrum is so weak that attempts to correct for the contami-

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1997PASP..109..270G

TABLE 1
Emission Lines Definitely Present in S Aps

Wavelength[a] (Å)	Identification	V_r (km s^{-1})	FWHM (km s^{-1})
5889.953[b]	NaI	-75	
5895.923[b]	NaI	-75	
6141.718	BaII	-93	
6496.896	BaII	-88	15
7065.276	HeI	-73	125
7664.907[c]	KI	-89	24
7698.979	KI	-86	26
8498.018	CaII	-81	27
8542.089[c]	CaII	-69	
8662.140	CaII	-71	26
	NaI	-187	

[a] from Moore,C.E. (1972)
[b] The very broad component has a velocity spread (half the base width) of 149 ± 10 km s^{-1} as estimated from the base width, and a radial velocity of -187 km s^{-1}
[c] blended with terrestrial OH lines

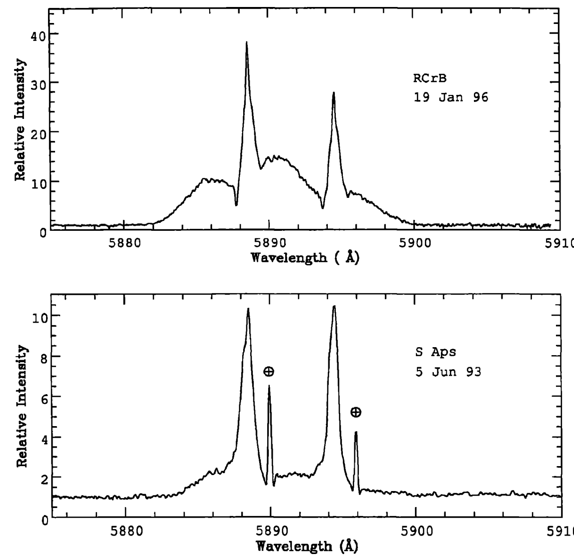

FIG. 1—Emission lines in the spectrum of S Aps at minimum light. The top panel shows the narrow K I resonance lines at 7664 and 7699 Å. The lower panel shows the He I broad emission line at 7065 Å. The continuum is principally scattered moonlight with telluric O_2 absorption lines in the upper panel. Night-sky OH emission lines are marked. The wavelength scale is that provided directly by the Th+Ar lamp.

nating moonlight were not successful. Hence, this note is restricted to a discussion of the strongest emission lines in the S Aps spectrum.

3. THE SPECTRUM: DISCUSSION

Published spectra of RCBs in decline show four components to the spectrum: the photospheric absorption spectrum, the narrow or chromospheric emission-line spectrum, the broad Na I D lines characterizing cooler broad emission and the broad He and forbidden emission-line spectrum. The chromospheric spectrum appears at the onset of a decline with the level of excitation decreasing as the decline progresses. The broad Na D and He I lines appear about 4 mag below maximum, and forbidden lines are seen in a deep minimum about 6–7 mag below maximum. Our spectrum of S Aps in decline shows representatives of each of the three emission-line components, as noted above.

Emission lines definitely present are listed in Table 1. Several are illustrated in Figs. 1 and 2. For the emission lines we list the radial velocity and the width (FWHM in km s^{-1}). All lines except the He I 7065 Å line and a component of the Na D lines are classified as "narrow." Inspection of Figs. 1 and 2 shows that the narrow lines are broader than the telluric lines and, hence, are resolved in this spectrum. The telluric lines have the same width as Th+Ar hollow cathode lines whose width is set by the spectrograph (10 km s^{-1} FWHM).

The radial velocity of a narrow line is measurable to a precision of about 1 km s^{-1}, as estimated from a comparison of the measured and known wavelengths of the night-sky OH lines. The mean velocity from the nine narrow lines is -81 ± 9 km s^{-1}. The line-to-line spread of 20 km s^{-1} is presumably a real difference. The stellar radial velocity as obtained from the absorption spectrum at maximum light is -78 km s^{-1} (Herbig 1993) and -65 ± 8 Kilkenny et al. (1992). The radial velocities obtained by Herbig (1993) on two successive days in 1992 April, show a difference of 8 km s^{-1} and Lawson and Kilkenny (1996) indicate the 1σ variation of 2.5 km s^{-1} from radial velocity. We thus adopt a stellar radial velocity of -72 ± 6 km s^{-1} in the following discussion.

The broad Na I D emission component is present in the spectrum (Fig. 2) and is blueshifted relative to the narrow

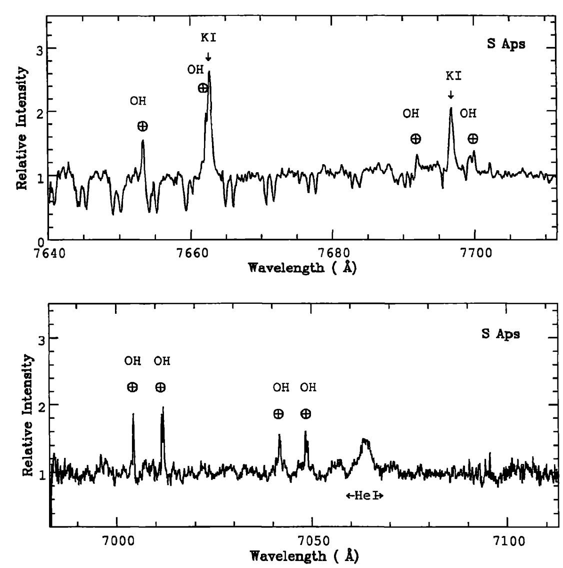

FIG. 2—The Na D emission feature in S Aps (lower panel) and in RCrB (upper panel). The wavelength scale for the S Aps spectrum is that provided directly by the Th+Ar lamp, i.e., the marked telluric Na emission lines are at their rest wavelengths. The RCrB spectrum, which was taken during the recent deep decline, has been shifted so that the narrow emission lines are at the observed wavelengths of the same components in the S Aps spectrum. Telluric Na emission is undetectable in the R CrB spectrum.

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1997PASP..109..270G

Na I emission line. We estimate the velocity spread of S Aps's Na I D broad component to be 149±10 km s^{-1} from the half-width at the base of the line.

In Fig. 2 we also show the Na I D profiles for RCrB from a spectrum taken at the McDonald Observatory during its recent and prolonged decline. This spectrum was taken at a resolving power of about 60,000. The two spectra have been aligned such that the narrow emission lines occur at the wavelengths. While the Na I D profiles for the two stars are similar—for example, both combine a narrow and a broad component—the S Aps profiles are distinctive in that the broad component appears blueshifted with respect to the narrow components. This shift is readily seen from the absence of broad-line emission in the interval 5896–5900 Å, i.e., to the red of the narrow D_1 line. Such emission is an obvious feature of the RCrB Na I D profile. We estimate the radial velocity of the broad Na I D component to be −187±10 km s^{-1} corresponding to a blueshift of 100 km s^{-1} with respect to the narrow components and the stellar velocity.

The broad-line hot component is represented by He I 7065 Å with a FWHM of 125±7 km s^{-1}. The He I line gives a radial velocity of −73 km s^{-1} which within the measurement errors is the same as the mean (−81 km s^{-1}) for the narrow lines and matches the stellar velocity.

Emission lines listed in Table 1 are certain identifications but they are also the expected lines based on the modest S/N ratio of this spectrum and the relative intensities of lines present in published spectra of the same wavelength interval (e.g., spectra of V854 Cen—Rao and Lambert 1993). Narrow emission lines which are predominantly low-excitation lines of singly charged ions are well represented in blue but not red spectra. Other emission lines of He I (e.g., 5876 and 6678 Å) are weaker in spectra of V854 Cen such that they would not be expected to be detectable in this spectrum of S Aps. Forbidden lines of [N II], [S II], and [O I] seen in V854 Cen and the recent decline of RCrB (unpublished observations) are not present in S Aps but, their absence is also not unexpected.

4. THE SPECTRUM: INTERPRETATION

The narrow emission-line spectrum is a common feature seen in the few RCBs observed in decline. When these lines make their first appearance after the star has faded by about 1 mag, the emission lines are often blueshifted by about 10 km s^{-1}. In S Aps, estimation of the shift between the "chromospheric" emission lines and the photospheric absorption lines is compromised by our inability to detect the photospheric spectrum. A low-resolution spectrum of S Aps at maximum with strong H and K lines of Ca II and very strong C_2 bands are shown in Kilkenny (1995). Limited data are available on the photospheric velocity and relatively large uncertainty of the emission-line velocity. The reported measurements indicate for a mean velocity of −72±6 km s^{-1}. The Na I D narrow lines (Fig. 2) are asymmetric. An asymmetry may be a common feature. Certainly the accompanying spectrum of R CrB shows a similar asymmetry but of opposite sign.

After correction for the instrumental profile, the (FWHM) widths of 12 (Ba II) to 25 (K I) km s^{-1} of the narrow emission lines, are too large by at least a factor of ten to be dominated by thermal broadening. There is, however, the tantalizing result that the intrinsic widths of the narrow lines and the He I (broad!) line satisfy approximately the square-root dependence on atomic weight expected for thermal broadening. The linewidths found here for S Aps are quite similar to those reported for the narrow lines of the decline spectra of other RCBs (Lambert et al. 1990).

Broad emission-line components have been seen in spectra of other RCBs in decline. Broad Na D lines have been reported for RCrB (Payne-Gaposchkin 1963; Cottrell et al. 1990), V854 Cen (Rao and Lambert 1993), and RY Sgr (Alexander et al. 1972). The widths are similar to that found here for S Aps. The distinguishing feature of the S Aps spectrum is the large blueshift of the Na D broad component: the shift of 98 km s^{-1} is equivalent to 0.7 of the component's half the base width. In the case of RCrB (two declines) and V854 Cen, the broad component is essentially at the photospheric velocity. This large blueshift is most simply attributed to a geometrical effect: for example, the emitting gas may be part of a bipolar flow with the receding jet obscured by the star or by the dust clouds.

It is presumed that the gas emitting the broad He I line is not the same gas that is emitting the Na I D lines. Coexistence of excited He atoms (or He ions, as the line is possibly formed by recombination) and Na atoms seems unlikely, even if the line profiles of He I and Na D lines gave the same radial velocity. However, such a possibility might occur in a shocked gas. The intensities of D_1 and D_2 are roughly equal suggesting that the gas is optically thick.

With the exception of the blueshifted Na D broad absorption, our spectrum shows that a cool RCB has the same general spectrum in decline as the warmer RCBs (R CrB, RY Sgr, V854 Cen) previously observed in decline. Although the available spectra of RCBs in decline remain few, the common spectral characteristics suggest a common geometrical structure with common underlying physics.

The chromospheric emission-line spectrum is an apparently universal feature of the spectrum of a RCB in decline. It may be reasonably supposed that this spectrum is a permanent feature but seen only when the much brighter photospheric spectrum is obscured by soot. The small blueshifts of the chromospheric lines which are a common feature of RCB declines suggest the chromosphere is mildly expanding. In S Aps, the emission lines are almost at the systemic value. But, if the chromosphere is spherically symmetric and large in radius relative to the photosphere, it is difficult to account for the apparently ubiquitous blueshift of the emission lines and, in particular, for the absence of redshifted emission from the chromospheric regions on the far side of the star. On the other hand, if the chromosphere is close to the star, it is difficult to explain why it too is not obscured by the soot—of course, in this picture, the star occults the regions on the far side. On the other hand dust could also be distributed in the form of asymmetric cloud disk in which case only limited portions of the chromosphere gets occulted. One may be forced to suppose that the chromosphere is enhanced in the region of the soot cloud. Perhaps, the enhancement occurs at the periphery of the cloud. Then, an expanding outer

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1997PASP..109..270G

atmosphere will necessarily show blueshifted emission lines in decline. (Jennings and Dyck 1972 assemble observations of normal late-type giants showing that stars with strong infrared emission from circumstellar dust grains have apparently weak chromospheric emission. Stencel et al. 1986 show that observations indicate a chromosphere is maintained even in the presence of considerable dust. These results do not necessarily exclude local enhancements of a chromosphere.) If, on the other hand, the emitting region is placed away from the star (in a disk of large radius, for example) and the site of soot formation, it becomes difficult to account for the blueshift and the excitation of the lines.

The Na D broad lines may be formed in an extended cool wind having a terminal velocity of 100–200 km s^{-1}. These lines may be excited by resonance fluorescence by undimmed photospheric light or excited locally through collisional excitation or radiative recombination. If the wind were spherically symmetric, the emitted broad line from those regions not blocked by the soot clouds would be approximately centered on the stellar velocity. To account for the observed blueshift of the broad Na D lines, it seems necessary to discard the assumption of spherical symmetry. A wind enhanced in opposing directions (say, an equatorial or a bipolar flow) and blocked asymmetrically by soot clouds will give emission lines shifted either to the blue or to the red. Apparently, the clouds at the time of our observation more severely obscured the receding arm of the flow.

There remains the case of the broad He I 7065 Å line. Since this is unshifted in velocity, it is presumably not emitted by the wind. Perhaps, it comes from hotter, more turbulent regions of the chromosphere that contributes the narrow lines. The presence of He I 3889 Å in U Aqr (Bond et al. 1979), another cool RCB star, as well as the presence of He I 7065 Å in S Aps indicate that the source of excitation cannot be radiative and is presumably collisional unless a hot unseen companion is invoked.

5. SUMMARY

The spectrum of the cool RCB S Aps in decline is quite similar to that of warm RCBs observed in similarly deep declines in all respects but one. The distinguishing mark of S Aps is that the broad component of the Na D lines is decidedly blueshifted with respect to the chromospheric lines and to the photosphere. This shift is attributed to formation of the lines in a nonspherically symmetric wind blocked asymmetrically by the soot clouds causing the decline.

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