THE UNUSUAL ULTRAVIOLET CHROMOSPHERIC SPECTRUM OF THE R CORONAE BOREALIS STAR, V854 CENTAURI (NSV 6708), AT MINIMUM LIGHT

GEOFFREY C. CLAYTON
Center for Astrophysics and Space Astronomy, Campus Box 389, University of Colorado, Boulder, CO 80309

BARBARA A. WHITNEY
Harvard-Smithsonian Center for Astrophysics, MS-15, 60 Garden Street, Cambridge, MA 02138

S. ADAM STANFORD
Department of Astronomy, University of California, Berkeley, CA 94720

JOHN S. DRILLING
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803

AND

P. G. JUDGE
High Altitude Observatory, 1850 Table Mesa Drive, P.O. Box 3000, Boulder, CO 80307

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ABSTRACT

The first IUE observations of a decline of the recently discovered R CrB star, V854 Cen, are reported. These observations are of particular interest because they include spectra taken at 7 mag below maximum light. This is the deepest minimum ever observed in an R CrB star with the IUE. The “chromospheric” emission spectra show striking differences from UV spectra of other R CrB stars in decline. In fact, the emission spectrum of V854 Cen at minimum light does not seem to have an analogue in any known emission-line object. Strong emission appears in several lines not normally seen in R CrB emission-line spectra, in particular at C ii] 42326, Mg i 28552, and C i λ2965, 2967. Spectral evolution similar to that seen in visible spectra of R CrB stars is clearly seen in the ultraviolet for the first time. The differences between V854 Cen and other R CrB stars may be related to known abundance differences or to different temperature and density conditions in the emission-line regions of the various R CrB stars. The emission may also be significantly affected by the presence of dust in or near the emitting region.

Subject headings: stars: chromospheres — stars: individual (V854 Cen) — ultraviolet: stars

1. INTRODUCTION

At maximum light, V854 Cen is the third brightest R Coronae Borealis (R CrB) star in the sky at 7th magnitude. However, V854 Cen was only discovered to be an R CrB star about 5 years ago (McNaught & Dawes 1986). These stars are best known for their deep minima at irregular intervals caused about 5 years ago (McNaught & Dawes 1986). V854 Cen seems to be more active than most R CrB stars. The episode reported here is the third major decline since 1987. This activity was a contributing factor to the late discovery of this star. It was generally fainter than 13th magnitude decline by 8 mag or more (Loreta 1934; O'Keefe 1939; Feast & Bateson 1991). Also, CH bands, not seen in other R CrB stars, are tentatively identified for V854 Cen (Kilkenny & Marang 1989). All R CrB stars seem to be pulsating variables (Lawson et al. 1990). Pugach (1977) suggests that pulsational phase is correlated with the onset of declines in RY Sgr. V854 Cen seems to pulsate with periods of 45, 70, and 110 days (Lawson, Cottrell, & Bateson 1991).

During the initial decline of an R CrB star, which takes a few days or weeks, the stellar continuum fades and is replaced by a “chromospheric” spectrum which itself fades away as the star reaches minimum light. In the 1988 decline of V854 Cen, Kilkenny & Marang (1989) found that at 6.5 mag below maximum, the visible emission spectrum was rich with lines of Ca ii, Sc ii, Ti ii, Fe i, Fe ii, Sr ii, Y ii, Zr ii, Na i D, and Hα, Hβ. Except for the Balmer emission, this spectrum is similar to that observed during declines of R CrB and RY Sgr (Cottrell, Lawson, & Buchhorn 1990; Alexander et al. 1972).

The ultraviolet (UV) spectrum also shows rich emission during a decline. Like the visible region, the UV spectra are made up of lines of Fe ii and Ti ii along with V ii, Cr ii, and Mg ii (Clayton et al. 1991). The observations of V854 Cen reported here are the first obtained with the International Ultraviolet Explorer (IUE). Most of the previous observations of R CrB stars have been at or near maximum light. IUE observations 3 or more magnitudes below maximum light are very rare (Evans et al. 1985; Holm et al. 1987; Clayton et al....
Five observations have been obtained with the IUE during the 1991 decline of V854 Cen, one at 3.5 and four at greater than 6 mag below maximum light. No IUE observations of any R CrB star have been obtained previously this far below maximum light.

2. OBSERVATIONS AND REDUCTIONS

The observations presented here were obtained with the IUE. All the spectra were obtained with the large aperture. The observations were made on 1991 March 19 (LWP 19951), 1991 April 14 (LWP 20141), 1991 April 15 (LWP 20150), 1991 June 5 (LWP 20527), and 1991 June 29 (LWP 20710, SWP 41954). The light curve for V854 Cen is shown in Figure 1 with the times of the IUE observations marked (Mattei 1991). The IUE data were reduced at the Regional Data and Analysis Facility at the University of Colorado. Absolutely calibrated spectra were produced from line-by-line IUE data files using the Optimal IUE data extraction software (Kinney, Bohlin, & Neill 1991). The spectra obtained March 19, April 14, and June 5 are plotted in Figure 2. Also plotted in Figure 2 for comparison are two spectra of RY Sgr taken during minima. The emission line at 2852 Å is saturated on LWP 20141 and LWP 20527. A three-point boxcar average has been applied to the data to match the resolution of the spectrograph (6 Å).

3. DISCUSSION

3.1. Line Identifications

Figure 2 shows a comparison of the V854 Cen spectra and two spectra of RY Sgr taken in similar declines. The V854 Cen spectra were taken 16, 42, and 94 days after the start of the decline, during the three local minima of the decline (see Fig. 1). The RY Sgr spectra are from declines in 1982 (Evans et al. 1985) and 1990 (Clayton et al. 1991). The first RY Sgr spectrum was obtained about 100 days into the 1982 decline, during the second of two local minima, when the star was 5 mag below maximum. The second spectrum was taken about four and a half magnitudes below maximum light, 41 days after the 1990 decline began, and just before minimum light. The lines were identified by comparing to the solar chromospheric limb spectra (Doschek, Feldman, & Cohen 1977), chromospheres of red giants (Judge & Jordan 1991; Carpenter, Wing, & Stencel 1985), and the slow nova RR Tel (Penston et al. 1983) which shows “nebular” (forbidden) lines of more highly ionized species. Both the RY Sgr spectra and the first V854 Cen spectrum are quite similar, showing many blended emission lines of Fe II, Ti II, V II, Cr II, and Mg II.

The most striking difference between the RY Sgr and V854 Cen spectra is the presence of strong emission around 2326 Å in V854 Cen. We identify this feature with the C II density-sensitive intersystem lines. No other known spectral feature can satisfactorily explain the observed emission (Baumert & Johnson 1984). This line is peculiar because it is not seen so strongly in any other R CrB star. The RY Sgr and R CrB decline spectra generally show only weak or no emission at this wavelength. These two stars and V854 Cen are the only stars of this class that have been observed significantly below maximum, where the continuum is low enough for an emission line to stand out assuming the source of the emission line to be independent of the cause of the decline. The resonance lines of C II λ1335 were reported by Holm & Wu (1982) in emission in both RY Sgr and R CrB at maximum light. It is the only obvious emission feature at maximum light (Holm et al. 1987). Our SWP observations obtained 94 days after initial decline show both C II λ1335 and C III λ1909.

Two other unusual lines are present at 2851.5 and 2965.5 Å in V854 Cen. The first line seems to be the resonance line of Mg I λ2852. Other identifications (e.g., Fe II UV 391) can be ruled out owing to the absence of other members of the multiplet. Moreover, these Fe II lines are photoexcited in giants by Hα, and other lines excited by the same mechanism (e.g., near 2505 Å) would be expected to be stronger. If the feature is indeed Mg I, then this suggests that the ion fraction Mg I/Mg II
is much higher in V854 Cen than in typical stellar chromospheres or RR Tel, for which Mg I is photoionized by the near-UV continuum (as seen in spectra of Penston et al. 1983). In V854 Cen, the unusual strength of Mg I might therefore result from an emission region which is shielded from near-UV radiation, perhaps by dust. Alternatively, the near-UV radiation might be very dilute.

The line at 2965 Å is intriguing. There is nothing listed at this wavelength in the solar limb spectrum, in red giant chromosphere spectra, or the RR Tel spectrum. We can discount Fe II lines (e.g., UV 78, UV 60), since other lines of these multiplets are absent. Given the strength of the carbon spectrum, one possible candidate is the 2s2p3S-2s2p1P transition of C I \( \lambda \lambda 2965, 2967 \). This identification has several points in its favor: it involves the same core transition as the C I] intersystem lines; other neutrals (Mg I, Na I) are seen in emission; and the transition is the lowest parity changing transition in C I, and is therefore likely to be strong in relatively low-density, low-electron density plasmas with a small background UV continuum. These lines have a critical electron density near 2 \( \times 10^9 \) cm\(^{-3} \), similar to the C I] lines (Mendoza 1983) and so provide an upper limit on the density in the emitting region. Given the absence of the C I resonance lines near 1657 Å, this would be an unlikely identification, except that electron temperatures may be extremely low (<5000 K) in the V854 Cen emission-line region (see § 3.3 below).

### 3.2. Spectral Evolution

The UV spectral evolution, most strongly seen in V854 Cen, is similar to that described by Alexander et al. (1972) in the visible. In the first spectrum obtained 16 days into the decline, Fe II multiplets UV 3, 4, 5, 32, 33, 34, 35, 36, 60, 61, and 64, are seen as well as multiplets UV 1, 2, 6, 62, and 63 which remain in the later spectra. The UV 4, 5, 32, 33, 34, 60, and 61 lines are excited by line leakage and are only seen in optically thick chromospheres (Brown, de M. Ferraz, & Jordan 1984; Judge & Jordan 1991). The disappearance of these lines between day 16 and 42 (Figs. 2c and 2d), indicates that the optical depth of the Fe II lines has been reduced. Possibly this is due to obscuration, by dust in our line of sight, of the lower chromosphere, where the column densities are higher. The V854 Cen observations were obtained in the three local minima within the 1991 decline. The rich spectrum was seen only in the first local minimum, while the simpler spectra were obtained in the second and third local minima. The second RY Sgr spectrum (Fig. 2b) is from the single minimum 1990 decline and agrees fairly well as an intermediate stage between the first two V854 Cen spectra.

Another unique feature of these spectra is that the Mg II \( \lambda 2800 \) doublet in the first V854 Cen spectrum is in absorption. This is the only UV spectrum during an R CrB star decline which shows Mg II in absorption. This may be because the spectrum was obtained so early in the decline (day 16). This is similar to the behavior of the Ca II H and K lines which appear first in absorption and did not go into emission until day 31 of the 1988 R CrB decline (Cottrell et al. 1990).

There are now some UV observations covering five declines in three R CrB stars. These will be described in greater detail in Clayton et al. (1991). Generally, the UV emission lines fade with time, but not nearly so fast as the visible emission lines. In visible spectra (Alexander et al. 1972; Herbig 1949; Payne-Gaposchkin 1963; Spite & Spite 1979), the emission is dominated by neutral and singly ionized metals. For example, in the 1990 decline of R CrB, there were no spectral changes in the visible before the decline began (Cottrell et al. 1990). After the star began to fade, the normal absorption spectrum began to fill in. By day 15 the chromospheric spectrum had appeared with Sc II, Ti II, and Fe II in emission. In the next few days, emission appeared in Na I D, Ba II, and Fe I, and by day 33, almost all the emission had disappeared except for the Na I D lines. At this time, Ca II H and K which had remained absorption lines began to show emission. There seems to be an exponential fading of the initial visible emission spectrum with a time constant of about 20 days. This spectral evolution seems to take place without any correlation to the behavior of the light curve in the decline. This evolution is apparent in the UV as well, where the Fe II lines are very strong to begin with, but progressively weaken with time. However, the C II], Mg II, Mg I, and C I lines in V854 Cen show little evidence of weakening over 5 months of this decline.

### 3.3. The V854 Cen Line-Emitting Region

There are real differences between the chromospheric spectra of V854 Cen and other R CrB stars. In particular, the strong C II] \( \lambda 2326 \), the strong lines at 2852 and 2965 Å, and the C I] \( \lambda 1909 \) line are not normally seen. There is no doubt that C II] \( \lambda 2326 \) is anomalously strong in V854 Cen. It is seen weakly in the second RY Sgr spectrum in Figure 2 and also may have been present in the 1989 decline of R CrB. V854 Cen has not been previously observed with IUE so it is not known if C II is visible at maximum light. Abundance analyses have been done for R CrB and RY Sgr (see Lambert 1986 for a review) but not for V854 Cen. However, it is evident from visible spectra of V854 Cen that it has a significantly higher hydrogen abundance than other R CrB stars. Perhaps, the carbon abundance is also higher in V854 Cen. Lines of C I] and Mg II ordinarily form in the same density and temperature regions of chromospheres (Judge 1986), so with the known overabundance of carbon and the strong Mg II emission, it is strange that C II] \( \lambda 2326 \) emission is not normally seen in other R CrB stars.

To investigate properties of the emission region, we have derived emission measure loci for the various lines for which reliable atomic data are available (Judge 1986). In Figure 3 we show emission measure loci for C II] \( \lambda 2326 \), Mg II \( \lambda 2800 \), Al II] \( \lambda 2670 \), and Si II] \( \lambda 1816, 2334 \), assuming a carbon abundance of 10.0 (solar: 8.7), and solar abundances (Allen 1973) for everything else (Lambert 1986). Varying the hydrogen abundance has no significant effect on the calculated emission measures. In typical stellar chromospheres, photoionization is extremely important, and usually the singly ionized atom dominates the ionization species for most electron temperatures (Judge 1986). The loci in Figure 3 were computed using this assumption. In this approximation, we infer the following: (1) the emission measure loci of Mg II, Si II, and C II are consistent only for electron densities near 2 \( \times 10^{10} \) cm\(^{-3} \). (2) The Al II] line suggests that the aluminum abundance might be lower than that adopted by an order of magnitude. (3) The C II] line has characteristic electron temperatures near 6000 K (as opposed to 10\(^4\) K). These temperatures are typical of the line-forming regions of red giants (Judge 1986).

In this picture, we have some outstanding problems: (1) What about the features at 2852 and 2965 Å? (2) It is difficult to understand aluminum abundances which are a factor of 10 lower than solar (Lambert 1986). (3) The derived electron density seems to be unreasonably high when com-
Fig. 3.—Emission measure loci diagram for V854 Cen, derived assuming that neutrals are strongly photoionized below 10^4 K (see text). Volume emission measures (units cm^-3) may be obtained by multiplying the emission measures shown by 1.4 x 10^{14}. Problems with these emission measures are discussed in the text.

pared to that seen in other low-gravity objects such as symbiotic stars or red giants. These problems suggest an alternative scenario in which the neutral metals are not as strongly photoionized as in cool giants, but instead, the ionization is controlled perhaps by collisions with electrons. As a first approximation, the photoionization rates depend on the ionization potentials of the neutrals. In order of increasing ionization potential (which are listed in eV, Allen 1973), the elements with lines observed in emission are: Na (5.14), Al (5.99), Mg (7.65), Si (8.15), C (11.26), and H (13.60). This alternative picture, which assumes collisional ionization, can naturally overcome points (2) and (3): The presence of substantial amounts of neutral magnesium and carbon can account for the 2852 and 2965 Å features, and the C ii emission measure will be higher than those plotted in Figure 3 owing to the lower fractional abundance of C ii. The electron temperature of the emitting region must be lower than say 6000 K, and the electron densities below roughly 10^7 cm^-3 in order that the C i lines near 2965 Å be stronger than the C ii resonance lines near 1675 Å. Moreover, this emission region might also account for the presence of the Na ii D lines in emission. The Al ii] emission measure remains a potential problem. Abundance analyses of R CrB and NY Sgr indicate solar abundances for aluminum (Lambert 1986). Also, the presence of C ii λ1335 and C m] λ1909 indicates that a higher temperature emitting region must exist.

The major unanswered questions about R CrB stars are how and where the dust is formed, and what is the source of the emission seen during declines. The observations reported here give clues to the answers to these questions. As seen in Figure 2, the C ii], Mg ii, Mg i, and C i emission remains relatively constant over 5 months and several dust formation episodes. This implies that this emission is constant and therefore is not produced in individual developing shock fronts and that it is not significantly extinguished by the dust formed in the decline. However, the source of the rich emission spectrum seen early in the decline may be eclipsed or changed by the forming dust. It has been suggested that dust must form at 10–20 stellar radii (Fadeyev 1988; Feast 1986) where the radiative equilibrium temperature reaches down to the condensation temperature of dust. Clayton et al. (1991) make empirical arguments for forming dust inside the chromosphere, perhaps in the wakes of the shocks. If enough dust did form inside the chromosphere it could drastically change the structure of the chromosphere (Bowen 1988; Willson 1988; Stencel, Carpenter, & Hagen 1986). The picture we have in mind is a large emitting region surrounding the star with dust forming in patches over the star interior to the emitting region. In a deep decline a dust patch in our line of sight expands to obscure the photosphere and a large part of the chromosphere. Infrared observations during declines indicate that the forming dust intercepts only a small fraction of the photospheric radiation (Forrest, Gillett, & Stein 1971; Glass 1978; Feast 1986). This picture is also in agreement with the spectropolarimetry taken at this time which shows large (about 10%) continuum polarization in the blue, decreasing across the emission lines (Whitney et al. 1991). Due to the patchy clouds between the emitting region and the photosphere, the amount of photoionization will vary throughout the emitting region. Certainly regions where the photospheric light is eclipsed might be the source for the collisionally excited lines. This idea of dust formation inside the "chromosphere" was put forward by Pagne-Gaposchkin (1963) and Coyne & Shawl (1973). More detailed modeling is beyond the scope of this paper. We are making a fuller analysis of these and other observations of V854 Cen and the R CrB stars that we hope will lead to a better understanding of the dust formation and emission from these mysterious stars.

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