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DO HYDROGEN-DEFICIENT CARBON STARS HAVE WINDS?

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ABSTRACT

We present high resolution spectra of the five known hydrogen-deficient carbon (HdC) stars in the vicinity of the 10830 Å line of neutral helium. In R Coronae Borealis (RCB) stars the He I line is known to be strong and broad, often with a P Cygni profile, and must be formed in the powerful winds of those stars. RCB stars have similar chemical abundances as HdC stars and also share greatly enhanced ^{18}O abundances with them, indicating a common origin for these two classes of stars, which has been suggested to be white dwarf mergers. A narrow He I absorption line may be present in the hotter HdC stars, but no line is seen in the cooler stars, and no evidence for a wind is found in any of them. The presence of wind lines in the RCB stars is strongly correlated with dust formation episodes so the absence of wind lines in the HdC stars, which do not make dust, is as expected.

Key words: stars: AGB and post-AGB – stars: carbon – stars: evolution – stars: variables: other

1. INTRODUCTION

The hydrogen-deficient carbon (HdC) stars are a very small class of carbon stars with very weak (or absent) hydrogen lines. Chemically they are completely distinct from the more common R- and N-type carbon stars. However, their abundances closely resemble a rare but better observed group of peculiar carbon stars, the R Coronae Borealis (RCB) stars (Warner 1967; Lambert 1986). RCB stars vary enormously in visual brightness, in a characteristic manner, but at irregular time intervals, due to their intermittent episodes of dust formation (Clayton 1996). In contrast, HdC stars have only weak brightness variations due to pulsations (Kilkenny et al. 1988; Lawson & Cottrell 1997). None of the HdC stars has shown any evidence for dust formation. As described in Brunner et al. (1998), RCB and HdC stars are spectroscopically similar, having the same abundances, effective temperatures, and absolute luminosities. However, the HdC stars lack the large visible brightness variations, IR excesses, and emission lines seen in the RCB stars, which are associated with mass-loss and dust formation. Only five HdC stars are known (Warner 1967), but as they are bright stars (all are in the HD catalog), it is likely that there are many more in the Galaxy (Warner 1967; Drilling 1986). The latter is also true of the RCB stars, of which only about 50 are known in the Galaxy (Clayton 1996; Zaniewski et al. 2005; Tisserand et al. 2008).

The origin of RCB stars has long been debated. The leading candidates appear to be (1) the merger of a C/O white dwarf and a He white dwarf, in which the merged object undergoes an episode of helium burning that creates an extended atmosphere around the degenerate core (the so-called double-degenerate (DD) scenario; Iben & Tutukov 1984; Webbink 1984) and (2) a late or very late He-shell flash that blows up an isolated incipient white dwarf into a "born-again" cool supergiant (Iben et al. 1996).

The similar chemical abundances of HdC and RCB stars have long suggested that the two classes of stars are evolutionarily linked. Stronger evidence for a link was established recently when Clayton et al. (2005, 2007) discovered that both HdC stars and RCB stars have huge overabundances of ^{18}O, with ^{16}O/^{18}O close to and in some cases less than unity (the solar and interstellar ratios are ~500). García-Hernández et al. (2009) have recently confirmed the low values of ^{16}O/^{18}O in several of the stars observed by Clayton et al. (2007). Such values are not approached in any other class of stars. For several reasons, including the observed low ^{16}O/^{18}O ratios, the late He-shell flash scenario seems unlikely to be the origin of RCB stars, and thus also unlikely to be the origin of the HdC stars (Clayton et al. 2007; García-Hernández et al. 2009). Therefore, it is important to explore the suggestion that these stars are created in the mergers of white dwarf binaries. The initial modeling results are promising; conditions where material is accreting onto the more massive C/O white dwarf appear to be favorable for the production of copious amounts of ^{18}O (Clayton et al. 2007).

If the double degenerate merger hypothesis is correct, then the question arises whether the HdC and RCB stars are formed by different types of merger events or represent an evolutionary sequence. Interestingly, the HdC stars all have lower values of ^{16}O/^{18}O (i.e., more enhanced ^{18}O) than RCB stars observed to date (Clayton et al. 2007). One might envision an evolutionary sequence in which the RCB stars represent an earlier and more turbulent post-merger phase, with less ^{18}O mixed to the photosphere and strong stellar winds, while HdC stars are a later phase when the winds have died down and mixing of ^{18}O into the photosphere is complete. On the other hand, it may be that the details of the merger process itself and/or the precise white dwarf masses create different degrees of ^{18}O enhancement and the different types of wind environments. It is also possible that HdC stars are, in fact, RCB stars where the dust formation process has turned off temporarily. Some RCB stars show very little dust formation; e.g., XX Cam has shown only one small dust formation event in the last 60 years (Yuin 1948; Rao et al. 1980).

2. THE HE 10830 Å LINE AS A PROBE OF THE WIND

Clayton et al. (2003) observed the He I line at 10830 Å in ten RCB stars. This line corresponds to the allowed $2^3P_{2,1,0}$–2^3S_1 transition and has two closely spaced components at 1.0833217 μm and 1.0833306 μm and a third component at 1.0832057 μm (all three wavelengths are in vacuo) which is

Table 1
Observing Log

Name	Type	T_{eff} (K)	V_{hel} (km s^{-1})[a]	UT Date	Telescope	Calibration Star
HD 137613	HdC	5400[b]	+56	2008 Feb 4	Gemini S	HIP 74493
HD 148839	HdC	6500[c]	−24	2004 Feb 7	Gemini S	HIP 81873
HD 173409	HdC	6100[b]	−69	2008 Apr 4	Gemini S	HIP 93667
HD 175893	HdC	5500[b]	+44	2008 Apr 4	Gemini S	HIP 93367
HD 182040	HdC	5600[b]	−46	2008 Apr 6	Gemini S	HIP 98953
FQ Aqr	EHe		+16	2008 Apr 11	Gemini S	HIP 102631
BD +23° 2998	R2		−32	2008 Jun 29	UKIRT	HIP 79332
TYC 1021	C		+11	2008 Jun 29	UKIRT	HIP 79332
BD +17° 3325	R0		−49	2008 Jun 29	UKIRT	HIP 79332
XX Cam	RCB	7250[d]	+12	2009 Jan 8	UKIRT	HIP 16599

Notes.
[a] Values derived from these spectra, except for FQ Aqr.
[b] Asplund et al. (1997).
[c] Lawson et al. (1990).
[d] Asplund et al. (2000).

generally much weaker than either of the other components. Thus in most astronomical cases the line is effectively a doublet. The 2^3S level is metastable and cannot radiate to ground or be radiatively excited from the singlet (1S) ground state. The $n = 2$ levels can be populated from below by collisional excitation (collision energies >20 eV for the 2^3S level) or from above by radiative decay such as would occur following recombination of He II. Ionization of He I to He II requires either collisions or photons of energy >24 eV; the latter seems unlikely in view of the lack of ultraviolet radiation in the line-forming regions of RCB and HdC stars. Collisions with sufficient energy could be present in shocks or where the gas in the wind is being accelerated by dust grains.

Clayton et al. (2003) have shown that most, if not all, RCB stars possess strong winds. On the other hand, the existence of winds in HdC stars has not been stringently tested. All that is known is that the dust clouds responsible for the huge light variations in RCB stars, which first form and then dissipate, are not present in HdC stars. In RCB stars the He I absorption lines are usually broad and blueshifted (Clayton et al. 2003), implying hot expanding gas with velocities of several hundred km s^{-1}, far greater than the escape velocities. From optical spectroscopy Rao et al. (2006) have shown that in R CrB itself the wind starts in the photosphere and is heated and accelerated as it moves outward. The winds observed in the RCB stars are strongly correlated with dust formation episodes that produce large declines in visible brightness (Clayton et al. 2003, G. C. Clayton et al. 2009, in preparation). During such an episode the He I absorption is sometimes accompanied by a redshifted P Cygni emission feature. However, the wind line weakens or disappears within a few days or weeks of the ends of the decline and the return of the star to maximum light (G. C. Clayton et al. 2009, in preparation).

Because the He 10830 Å line can reveal and characterize the winds in carbon-rich stars, we have used the Gemini South telescope to obtain high resolution spectra in the vicinity of this line in the five known HdC stars. The spectra allow a direct comparison between the winds of the two classes of objects and thus directly address the relationship between the classes. A second motivation for this study is to investigate the nature of the wind driver. It has been suggested that the winds in RCB stars are dust driven (Clayton et al. 1992). If there are also winds in their dustless cousins, the HdC stars, then another driving mechanism must exist.

3. OBSERVATIONS AND DATA REDUCTION

Spectra in the vicinity of the He I 10830 Å line were obtained for the five known HdC stars on 2008 February 4 and 7 and April 4 and 6 at the Gemini South telescope, using the echelle spectrograph Phoenix, as part of Gemini program GS-2008A-Q-17. A log of these and additional observations is given in Table 1. The 0.″34 slit was used and provided a resolving power of ~50,000. Each star was positioned alternately at two locations along the slit. Total integration times were typically a few minutes. The extreme helium (EHe) star, FQ Aqr, which is expected to have a prominent 10830 Å line, was also observed at Gemini South on 2008 April 11. EHe stars, which are low mass A or B supergiants with strong helium lines and weak or absent hydrogen lines, appear to be higher temperature counterparts of RCB and HdC stars (Pandey et al. 2001; Jeffery 2008). The wind characteristics of the EHe stars are not known.

Spectra of bright main sequence stars of spectral types A0–A2 were obtained near-simultaneously to and at similar airmasses as those of the HdC and EHe stars in order to remove telluric lines from the HdC and EHe stellar spectra and to provide wavelength calibration via the same telluric lines. The wavelength calibration is accurate to better than 3 km s^{-1}. A few of the A stars possessed weak 10830 Å lines, which were artificially removed by interpolation prior to ratioing.

To obtain further comparisons, we used the United Kingdom Infrared Telescope (UKIRT) and its facility echelle spectrograph, CGS4 to obtain spectra of three normal carbon stars, TYC 1021 and BD +17° 3325, and BD +23° 2998, that are not expected to have winds and for which the He line should be weak or altogether absent. These stars were observed on 2008 June 29, as part of the UKIRT Service Program, with CGS4's narrow slit, which provided a resolving power of ~35,000. A further UKIRT Service observation of the inactive RCB star XX Cam was obtained on 2009 January 8. All of the UKIRT spectra were reduced in the manner described above.

4. RESULTS

Figure 1 contains the spectra of the five HdC stars along with the comparison hot carbon star BD +17° 3325 (top) and cool carbon star TYC 1021 (bottom). The HdC stars in Figure 1 are arranged in order of effective temperature (see Table 1 for values). For most of these stars several wide-ranging values of T_{eff} exist in the literature and thus the ordering may not be exact.

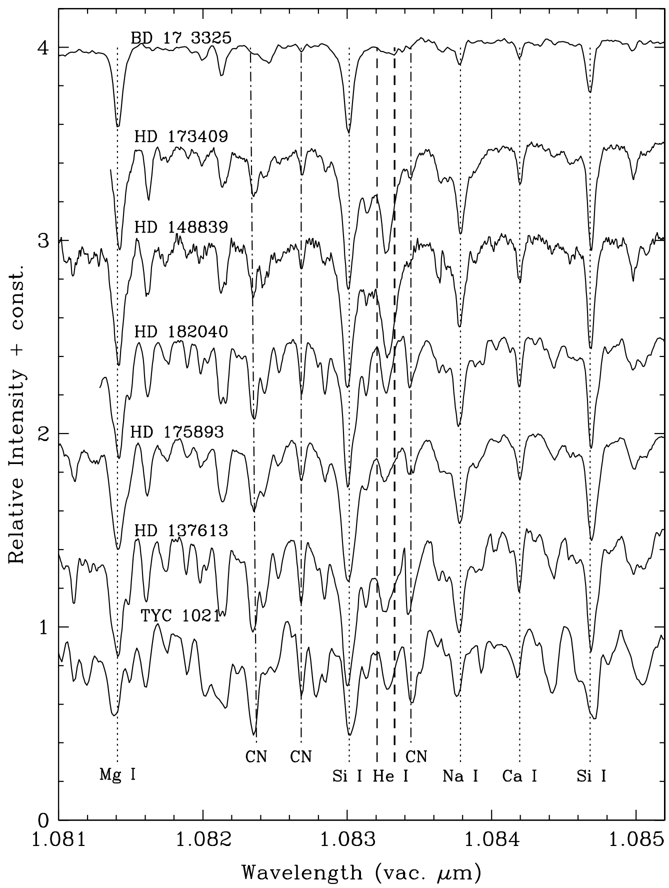

Figure 1. 1.081–1.085 μm spectra of the five HdC stars and two normal carbon stars (at top and bottom), offset vertically in steps of 0.5. The spectra are arranged in rough order of $T_{\rm eff}$, with hotter stars at the top. Some of the stronger lines are identified at bottom, and the wavelengths of the He I "doublet" are also shown.

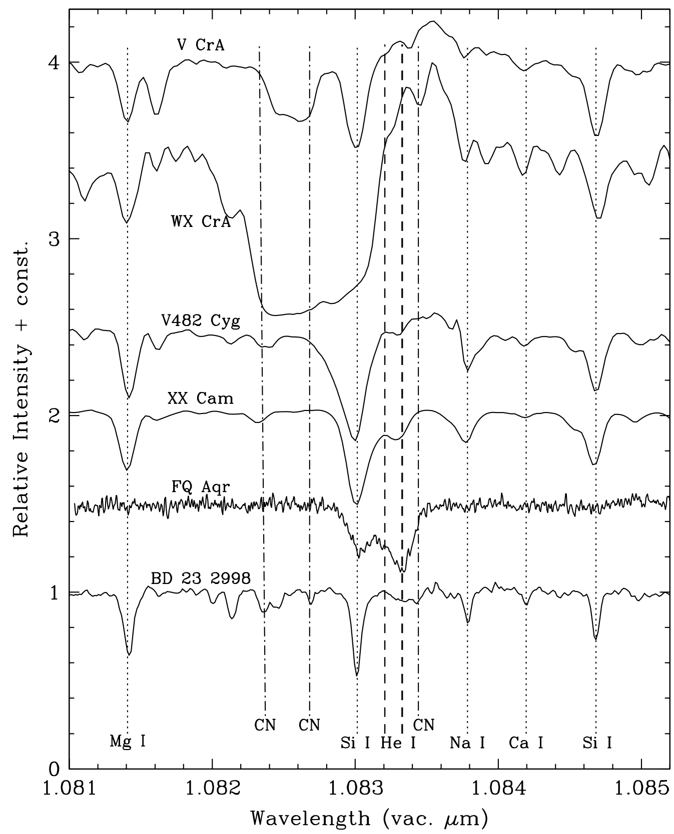

Figure 2. 1.081–1.085 μm spectra of the active RCB stars V CrA, WX CrA, and V482 Cyg (from Clayton et al. 2003), the inactive RCB star XX Cam, the EHe star FQ Aqr, and the hot carbon star BD +23° 2998 offset vertically in steps of 0.5 or 1.0 (for WX CrA).

The wavelengths of several atomic lines, including the He I doublet, are identified in both figures, as well as some of the numerous lines of CN. The wavelengths and identifications are from Hirai (1974), Wallace et al. (1993), and Hinkle et al. (1995). With the exception of FQ Aqr, the spectra have been shifted in wavelength to provide best overall matches to the atomic lines. The derived heliocentric radial velocities for the newly observed stars are listed in Table 1. Small deviations are present from line to line, but the overall accuracy of the fit is about 3 km s^{-1}. The radial velocities of the HdC stars are systematically about 12 km s^{-1} more negative than those in Lawson & Cottrell (1997). However, measurements of HD 137613 and HD 148839 at other wavelengths yield velocities within 2 km s^{-1} of the values in the table (N. K. Rao, unpublished data), and thus we are confident of our values.

Figure 2 shows the spectra of the "normal" RCB stars, V CrA, WX CrA, and V482 Cyg from Clayton et al. (2003), the currently inactive RCB star XX Cam, the EHe star (FQ Aqr), and another comparison carbon star, BD +23° 2998. V CrA and WX CrA show broad and complex P Cygni He I profiles typical of the winds seen in RCB stars during declines. RCB stars that have gone a very long time without a decline at the time of the He I observation show weaker He I wind profiles (e.g., V482 Cyg) and in the case of XX Cam, a spectrum very similar to the HdC stars with no evidence for the presence of a wind.

The spectrum of each of the three cooler HdC stars (HD 137613, HD 175893, and HD 182040) in Figure 1 is a close match to the spectrum of the cool carbon star TYC 1021, not only in terms of the lines present but also in terms of the relative strengths of the lines. The spectra of the two hotter HdC stars (HD 173409 and HD 148839) appear to be intermediate between TYC 1021 and the two hotter carbon stars, BD +17° 3325 (Figure 1) and BD +23° 2998 (Figure 2). All of these spectra contrast strongly with that of the EHe star, FQ Aqr (Figure 2). The broad and blended absorptions in that star must both be due to He I. The shorter wavelength absorption component centered at 1.08301 μm corresponds in wavelength to a Si I line, but the other Si I line in the spectrum is absent. The longer wavelength component is consistent with the stellar radial velocity determined by Pandey et al. (2001). FQ Aqr thus has a broad He I absorption centered on the stellar velocity and broad shell-like feature with a characteristic velocity shift of ~90 km s^{-1}.

Clearly the spectra of the HdC stars also contrast strongly with the RCB stars V CrA, WX CrA, and V482 Cyg, in that none of them possesses a strong and broad He I line. They more closely resemble XX Cam, but have stronger CN lines. An absorption feature centered between the wavelengths of the He I doublet is present in the spectra of the HdC stars and in XX Cam, but it is narrow. It is also weak in the cooler HdC stars. The wavelength of this feature corresponds to a line of CN; however, CN lines in XX Cam at other wavelengths are very weak or absent (Pandey et al. 2004), which is not surprising due to its high temperature. Without a convincing identification and additional modeling it is unclear to what extent the helium line contributes to the feature.

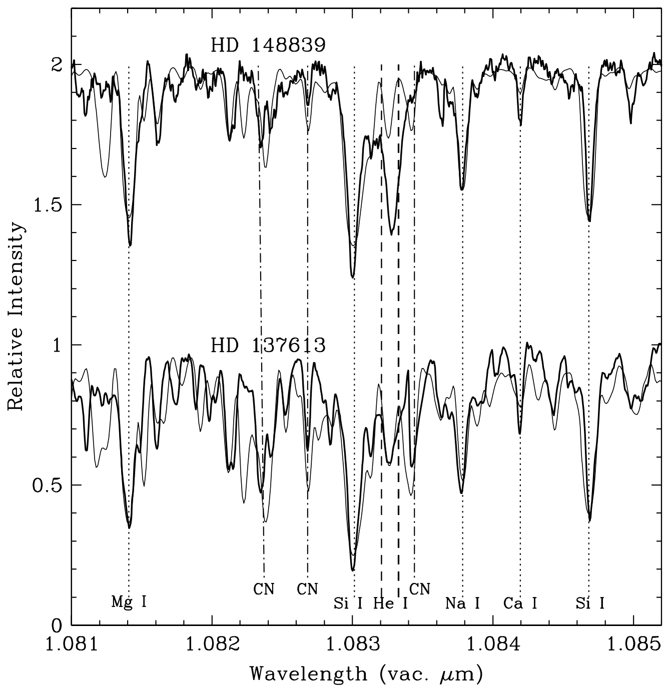

Figure 3. Observed (broad lines) and synthetic (narrow lines) spectra of the hot HdC star HD 148839 and the cool HdC star HD 137613, vertically offset by 1.0 units. See the text for details of models.

5. COMPARISONS WITH MODEL SPECTRA

Figure 3 shows comparisons of the spectra of the cool HdC star HD 137613 and the hot HdC star HDC 148839 with synthetic spectra. The synthetic spectra, kindly produced by D. A. García-Hernández, used MARCS model atmospheres for hydrogen-deficient stars, with scaled solar abundances and C/He = 0.01, and included atomic lines (with the exception of He) from the Vienna Atomic Line Database, as well as a molecular line list supplied by Plez. The values of T_{eff}, log g, and the abundances are the same as used by García-Hernández et al. (2009).

The agreement of the synthesized spectrum with that observed for HD 137613 ($T_{\mathrm{eff}} = 5400$ K, log $g = 0.5$) is generally good. The Si I, Ca I, Mg I, and Na I lines match quite well and the molecular (CN) features in the vicinity of the He I line match fairly well. Only two prominent lines, near 1.0812 μm and 1.0822 μm do not have counterparts in the model, but they are far from the He I wavelengths. Thus it is clear that little or no He I absorption is present in HD 137613.

The same line list and parameters were used to synthesize the spectrum of HD 148839, using a model with $T_{\mathrm{eff}} = 6500$ K and log $g = 0.5$. The match is about as good as that for HD 137613, except near 1.0833 μm. Here there is an extra feature that the model does not reproduce. Increasing the strength of the weak CN line at this wavelength leads to large disagreements at other wavelengths, and indeed is probably unrealistic since the CN line should be slightly stronger in the cooler HD 137613. Similarly the strengths of weak lines of Si I and Ca I close to this wavelength cannot be increased without making the other lines of these species stronger than in the observed spectrum. A similar discrepancy between the synthetic and observed spectra is found for the other hot HdC star, HD 173409.

We are uncertain as to the identity of this extra feature in HD 148839. If it is He I, it is blueshifted from the dominant red member of the doublet by about 15 km s^{-1}. Thus it would not be the typical wind line that is seen in RCB stars. However, if it is He I it also could not be due to photospheric absorption, because of the velocity shift. If due to He I, the small blueshift would be similar to that of some narrow emission lines which are seen in RCB stars during declines (Alexander et al. 1972; Cottrell et al. 1990; Rao et al. 1999; Skuljan & Cottrell 2002).

6. CONCLUSION

The spectra presented here make it clear that just as HdC stars do not have the dramatic light curves and IR excesses of their cousins, the RCB stars, so also do not possess winds even remotely close in strength to RCB stars. This result is consistent with the idea that the winds in RCB stars are dust driven, which has received recent support from the observation that the winds weaken with increasing time after the most recent decline in visual brightness (G. C. Clayton et al. 2009, in preparation). The HdC stars also have weaker pulsations than the RCB stars. This difference may play a role in the absence of winds and dust formation in the HdC stars.

Despite the remarkable similarities in their chemical abundances and their even more striking similarly isotopic anomalies, suggesting a common origin, these two types of stars behave quite differently. We suspect that understanding the differences between RCB and HdC stars will require detailed studies of the white dwarf mergers that appear to be the best explanation for their existence.

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