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HE 1015−2050: DISCOVERY OF A HYDROGEN-DEFICIENT CARBON STAR AT HIGH GALACTIC LATITUDE

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ABSTRACT

Medium-resolution spectral analysis of candidate Faint High Latitude Carbon (FHLC) stars from the Hamburg/ESO survey has given us the potential to discover objects of rare types. Two primary spectral characteristics of R Coronae Borealis (RCB) stars are hydrogen deficiency and weaker CN bands relative to C_2 bands. They are also characterized by their characteristic location in the $J-H$ and $H-K$ planes with respect to cool carbon stars. From a spectral analysis of a sample of 243 candidate FHLC stars, we have discovered a hydrogen-deficient carbon (HdC) star HE 1015−2050, at high Galactic latitude. A differential analysis of its spectrum with that of the spectrum of U Aquarii (U Aqr), a well-known cool HdC star of RCB type, provides sufficient evidence to put this object in a same group as that of U Aqr. Furthermore, it is shown that HE 1015−2050 does not belong to any of the C-star groups CH, C-R, C-N, or C-J. Cool RCB stars form a group of relatively rare astrophysical objects; approximately 51 are known in the Galaxy and some 18 in the Large Magellanic Cloud and five in the Small Magellanic Cloud. The present discovery adds a new member to this rare group. Although its spectral characteristics and its location in the $J-H$ versus $H-K$ plane place HE 1015−2050 in the same group to which U Aqr belongs, extended photometric observations would be useful to learn if there is any sudden decline in brightness, this being a characteristic property of HdC stars of RCB type.

Key words: stars: carbon – stars: chemically peculiar – stars: individual (HE 1015−2050) – stars: late-type – stars: low-mass

1. INTRODUCTION

Hydrogen-deficient carbon (HdC) stars are spectroscopically similar to the R Coronae Borealis (RCB)-type stars. While they may show small-amplitude light variations (Lawson & Cottrel 1997), the deep minima and infrared excesses that are characteristics of RCB stars are absent in these stars (Warner 1967; Feast & Glass 1973; Feast et al. 1997). These two groups have been collectively identified as HdC stars (Warner 1967). In spite of several studies, the formation mechanism(s) of these stars still remains poorly understood. Insight into this can be obtained through detailed studies of a large statistically significant number of these objects. However, as these objects are rare, in particular, only about 51 Galactic RCB stars are known so far; a search for these objects seems therefore extremely worthwhile.

HD 182040 is the first object to be identified as HdC star (Bidelman 1953). The recent surveys of the Large Magellanic Cloud (LMC; Alcock et al. 2001; Morgan et al. 2003) revealed that, unlike in the Galaxy, the RCB star population is dominated by cool stars rather than warm stars by 7:2. As the environment of LMC is more metal-poor than the solar neighborhood, it seems worth searching for HdC stars in the environment of lower metallicity (subsolar). The sample of Faint High Latitude Carbon (FHLC) stars from the Hamburg survey (Christlieb et al. 2001) offers such a possibility of being objects with small initial mass and possible lower metallicity. Medium-resolution spectral analyses of about 243 objects from this sample of 403 show that 161 of them exhibit strong C_2 bands in their spectra; their spectral characteristics are discussed in several papers (Goswami 2005; Goswami et al. 2006, 2007, 2010a, 2010b). In this Letter, we discuss the spectrum of HE 1015−2050; a careful inspection reveals the star to exhibit spectral characteristics of cool HdC stars. Furthermore, a differential analysis of the star's spectrum with the spectrum of U Aqr provides sufficient evidence to put this object in a group same as that of U Aqr. Apart from the very large strength of Sr II at 4077 Å and Y II at 3950 Å, U Aqr is a typical RCB-type variable and its high radial velocity (103 ± 20 km s^{-1}) indicates that it belongs to an old population and that its main-sequence progenitor had a mass $\sim 1\,M_\odot$ (Bond et al. 1979). These two features of Sr II and Y II are also observed in the spectrum of HE 1015−2050 and are very similar to those in U Aqr.

2. OBSERVATIONS AND DATA REDUCTION

The star HE 1015−2050 was observed with 2 m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Mt. Saraswati, Digpa-ratsa Ri, Hanle on 2009 December 5 and 2010 January 24, using Himalayan Faint Object Spectrograph Camera (HFOSC). The grism used in the present investigation and camera combination yielded a resolution of $\sim$1330 ($\lambda/\delta\lambda$) covering a spectral interval of 3800–6800 Å. Spectra of HD 209621, HD 182040, U Aqr, V460 Cyg, and ES Aql used for comparison were obtained during earlier observation cycles using the same observational set up. A spectrum of C-R star HD 156074 from Barnbaum et al.'s (1996) atlas, which has a comparable resolution to the present observations, has been used for comparisons. Wavelength calibration was accomplished using observations of a Th–Ar hollow cathode lamp. The CCD data were reduced using the IRAF software spectroscopic reduction packages. The photometric parameters of HE 1015-2050 and the comparison HdC and RCB stars are listed in Table 1.

3. SPECTROSCOPIC CONFIRMATION

The membership of a star to a particular group can be determined in terms of a number of parameters, spectral characteristics being an important one. In terms of spectral

Table 1
Photometric Parameters of HE 1015−2050 and the Comparison HdC and RCB Stars

Star No.	R.A. (2000)	Decl. (2000)	l	b	B	V	$B-V$	J	H	K
HE 1015−2050	10 17 34.232	−21 05 13.87	261.3144	29.0853	16.97	16.3	0.67[a]	14.977	14.778	14.504
HE 2200−1652 (U Aqr)	22 03 19.690	−16 37 35.29	39.1507	−49.8124	12.16	11.17	0.994	9.562	9.283	8.961
HD 182040	19 23 10.077	−10 42 11.54	26.8639	−11.8517	8.02	7.0	1.07	5.364	5.228	4.947
ES Aql	19 32 21.61	−00 11 31.00	37.4640	−09.1835	13.5	...	...	10.244	9.123	7.960

Note. [a] From Christlieb et al. (2001).

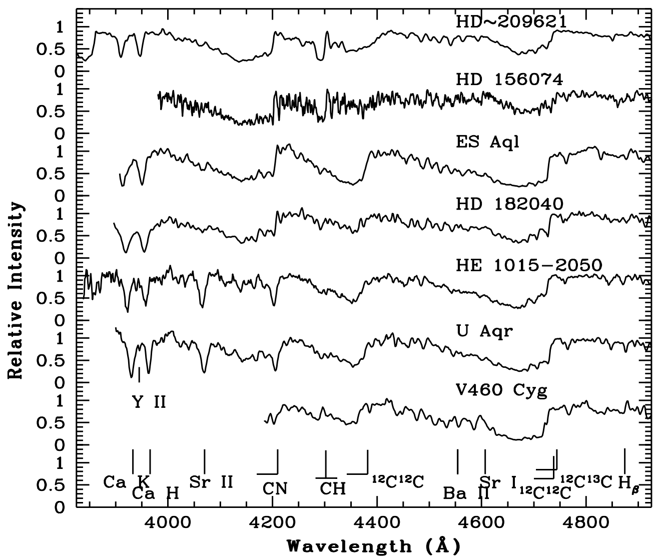

Figure 1. Comparison between the spectrum of HE 1015−2050 with the spectra of V460 Cyg (C-N star), U Aqr, ES Aql (cool HdC stars of RCB type), HD 182040 (a non-variable HdC star), HD 156074 (C-R star), and HD 209621 (CH star) in the wavelength region 3850–4950 Å. The *G* band of CH distinctly seen in the CH and C-R stars' spectra are barely detectable in the spectra of HE 1015−2050 and other HdC stars spectra. The large enhancement of Sr II at 4077 Å in the spectrum of U Aqr is easily seen to appear with almost equal strength in the spectrum of HE 1015−2050. Y II line at 3950 Å is detected in the spectra of both HE 1015−2050 and U Aqr. The most striking feature in the spectra of U Aqr and HE 1015−2050 is the strength of the Sr II λ 4215 line; this feature is inextricably blended with the nearby strong blue-degraded (0, 1) CN 4216 band head in HD 182040. The spectrum of HE 1015−2050 compares closest to the spectrum of U Aqr.

characteristics, the spectra of cool RCB stars show distinct C_2 molecular bands; these bands are weakly visible in the warm RCB stars. In Figures 1–3, we show a comparison of the spectrum of HE 1015−2050 with the spectra of two cool RCB-type stars U Aqr and ES Aql, a well-known non-variable HdC star HD 182040, a well-known CH star HD 209621, and a C-N star V460 Cyg in the wavelength regions 3850–4950, 4900–6000, and 5950–6700 Å, respectively. Some of the key spectral features considered for the classification of the program stars are the strength of *G* band of CH around 4310 Å, the presence or absence of isotopic bands of C_2 and CN, the Swan bands $^{12}C^{13}C$ and $^{13}C^{13}C$ near 4700 Å, other C_2 bands in the 6000–6200 Å region, and the ^{13}CN band near 6350 Å. In particular, we have used hydrogen deficiency and the relative strength of C_2 bands in the 6000–6200 Å region and the CN bands near 6206 Å and 6350 Å as important classification criteria. As the Balmer lines are weak in carbon stars, the strength/weakness of CH band in C-rich stars provides a measure of the degree of hydrogen deficiency.

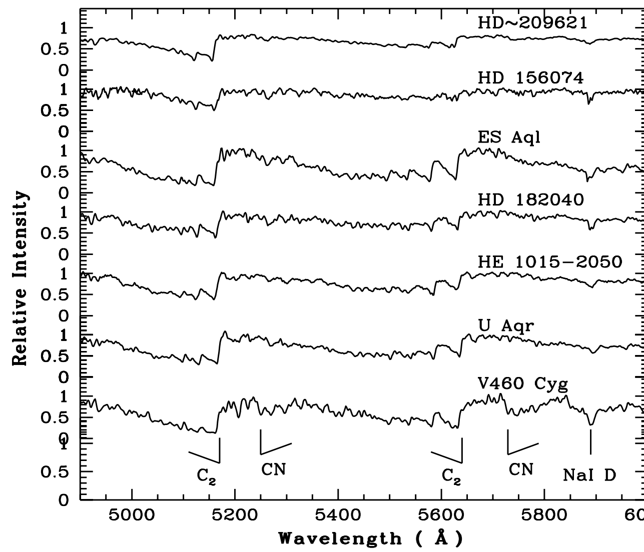

Figure 2. Same as Figure 1 except for the wavelength region 4900–6000 Å. The weakness of CN bands relative to the C_2 bands in the spectra of HE 1015−2050 and other HdC and RCB stars is noticeable. The features due to Na I D, although appearing strong in HE 1015−2050 and U Aqr, are much weaker relative to their counterparts in V460 Cyg and HD 182040. The HE star's spectrum bears a resemblance closest to the spectrum of U Aqr.

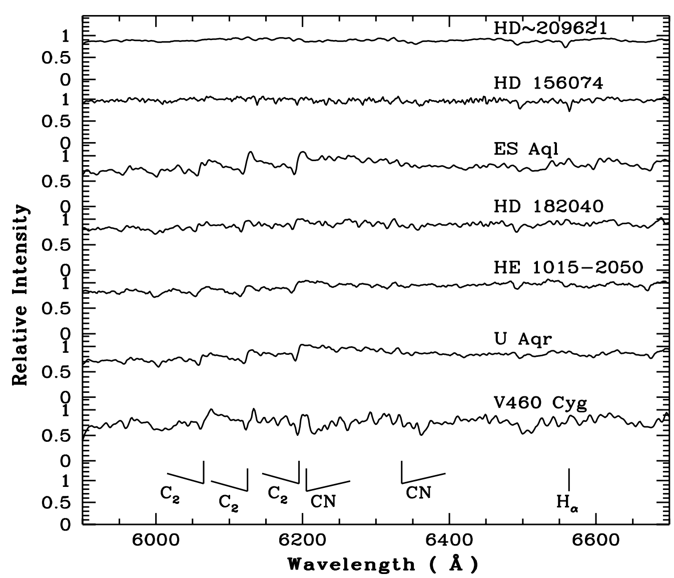

Figure 3. Same as Figure 1, except for the wavelength region 5900–6700 Å. The CN bands which appear with almost equal strengths in the spectrum of the CN star V460 Cyg are almost absent (or barely detectable) in the spectra of HE 1015−2050 and U Aqr. H$_\alpha$ feature is distinctly seen in the spectra of the CH and C-R stars HD 209621 and HD 156074, respectively. This feature is not detectable in the spectra of HE 1015−2050, HdC, and RCB stars. Non-detection of H$_\alpha$ and marginal detection of *G* band of CH (Figure 1) hint at hydrogen-poor nature of the objects.

3.1. *Spectral Characteristics: Hydrogen Deficiency*

An inspection of the spectra in the *G*-band region (Figure 1) shows that this feature which is strongly seen in CH and C-R stars' spectra is marginally detected in the spectrum of HE 1015−2050. The *G*-band strength is about equal or weaker relative to its counterpart in the spectra of the HdC star HD 182040 and the two HdC stars of RCB-type U Aqr and ES Aql. H_β feature, which is generally seen in the spectra of C-R and C-N stars, is not clearly detectable in the spectra of the HdC stars HD 182040, U Aqr, ES Aql, and HE 1015−2050. Marginal detection or non-detectability of H_β feature could also be one of the evidence for hydrogen deficiency in U Aqr, ES Aql, HD 182040, and HE 1015−2050.

H_α feature which is distinctly seen in the spectra of CH star HD 209621 and C-R star 156074 is also not detectable in HE 1015−2050, HD 182040, U Aqr, and ES Aql (Figure 3). In the case of some cool carbon stars, if not hydrogen-poor, the Balmer lines show up in chromospheric emissions. Such chromospheric feature is absent in the spectrum of HE 1015−2050. This again hints at the hydrogen-poor nature of the star.

3.2. *Spectral Characteristics: Molecular Bands of C_2 and CN*

One of the spectral characteristics which seems to be shared by all cool HdC stars of RCB type including U Aqr is that the red CN bands are usually much weaker even in stars with strong C_2 bands (Lloyd Evans et al. 1991; Alcock et al. 2001; Morgan et al. 2003). These characteristics differentiate RCBs from other carbon stars. The spectrum of HE 1015−2050 is dominated by the blue-degraded Swan system of C_2 bands. As in the case of U Aqr, a carbon molecular band head around 6191 Å is seen strongly in HE 1015−2050; this feature is much weaker in HD 182040. As seen in Figure 3, in the spectrum of C-N star V460 Cyg, the C_2 bands around 6000–6200 Å and CN bands around 6206 Å and 6350 Å appear almost of equal strength. Although C_2 band depths in the spectra of HE 1015−2050 and the two HdC stars of RCB type are similar to those in V460 Cyg, the red-degraded CN bands appear much weaker. CN bands are clearly weaker in U Aqr's spectrum; in the spectrum of HE 1015−2050, these bands are even weaker than in U Aqr. The presence of (6,2) λ6500 CN band is unlikely. Metal lines near 6500 Å including Ba II at 6496 Å and also a C_2 band (4,7) λ6533 are likely to contribute to the appearance of the spectrum around that region. The bands (4,0) CN λ6206 (Figure 3), (6,1) CN λ5730, and (7,1) CN λ5239 (Figure 2) are almost absent in the HE star's spectrum; these bands are also very weak or absent in the normal RCB stars. The red isotopic bands involving ^{13}C are not normally present in RCB stars (Lloyd Evans et al. 1991). As expected in RCB stars, the (1,0) $^{13}C^{12}C$ λ4744 band is present in HE 1015−2050, but much weaker than the (1,0) $^{12}C^{12}C$ λ4737 band. The RCB stars are reported to show the strong blue-degraded (0,1) CN 4216 member of the violet band system. The spectral region of HE 1015−2050 shortward of 4216 Å bears a striking similarity with the spectrum of U Aqr. The above spectral characteristics can also be seen in other cool Galactic RCB stars, e.g., Z UMi and S Aps (Benson et al. 1994; Goswami et al. 1997a, 1997b, 1999) and stand in favor of HE 1015−2050's membership to the cool RCB group.

3.3. *Non-membership of HE 1015−2050 in CH, C-R, C-N, and C-J Groups*

We have further examined the spectrum of HE 1015−2050 for its possible membership in any of CH, C-R, C-N, and C-J groups. Following the carbon stars classification schemes and spectral criteria (Keenan 1993; Barnbaum et al. 1996; Keenan & Barnbaum 1997; Goswami 2005), we have shown that the star HE 1015−2050 does not belong to any of CH, C-R, C-N, and C-J groups.

In the spectra of CH and C-R stars, the CH band around 4310 Å, H_β, and H_α features are prominently seen. In Figures 1 and 3, a marginal or weak detection of these features in the spectrum of HE 1015−2050 therefore is a strong indication that it does not belong either to CH or C-R group.

The red-degraded CN bands around (6,1) λ5730, (7,2) λ5860, (4,0) λ6206, and (5,1) λ6335 are usually seen as prominently as the C_2 bands in C-N stars. Weaker CN bands in the spectrum of HE 1015−2050 suggest that the star is not a conventional C-N star. As seen in Figure 1, Ba II at 4554 Å and Sr I at 4607 Å which are seen quite distinctly in the spectrum of the C-N star V460 Cyg could only be marginally detected in the spectra of HE 1015−2050 and U Aqr spectra. C-N stars are characterized by strong depression of light in the violet part of the spectrum (i.e., V460 Cyg in Figure 1). The cause of rapidly weakening continuum below about 4500 Å is believed to be due to scattering by particulate matter; but this idea is not yet fully established. Blue/violet part of the spectrum in HE 1015−2050 (and also of U Aqr) is accessible to observation and atmospheric analysis. As seen from Figure 1, features due to CaK, CaH, Y II, and Sr II that are not seen in the spectrum of V460 Cyg are observable with almost equal strengths in the spectra of U Aqr and HE 1015−2050. In these respects, the star HE 1015−2050 could not be classified as a C-N star.

The possibility of HE 1015−2050 belonging to C-J group is ruled out by the absence of the blue–green Merrill–Sanford (MS) bands of SiC_2. MS red-degraded bands are generally prominently seen in C-J stars. In the spectrum of HE 1015−2050, MS bands of SiC_2 at 4640 Å and 4977 Å both could not be detected. Thus, we see that HE 1015−2050 does not belong to any of the C-star groups CH, C-R, C-N, and C-J.

3.4. *Atmosphere of HE 1015−2050*

The stellar atmosphere of HE 1015−2050 has comparable effective temperature as those of cool RCB-type stars. The estimated effective temperature ($T_{\rm eff}$) of HE 1015−2050 ∼ 5263 K derived using semi-empirical temperature calibration relations offered by Alonso et al. (1994, 1996, 1998) is similar to the estimated $T_{\rm eff}$ ∼ 5000 K for cool Galactic RCB stars known, e.g., S Aps, WX CrA, and U Aqr (Lawson et al. 1990).

Carbon isotopic ratio $^{12}C/^{13}C$, widely used as a mixing diagnostics, provides an important probe of stellar evolution. These ratios measured on medium-resolution spectra, although not accurate, provide a fair indication of the evolutionary stages. Using the molecular band depths of (1,0) $^{12}C^{12}C$ λ4737 and (1,0) $^{12}C^{13}C$ λ4744, we have estimated the ratio $^{12}C/^{13}C$ to be ∼6.4 in HE 1015−2050 and ∼3.4 in U Aqr. In the spectrum of HD 182040, the (1,0) $^{12}C^{13}C$λ4744 band is not observed.

Atomic lines. Similar to U Aqr, the spectrum of HE 1015−2050 is characterized by an extraordinary strong line of Sr II at 4077 Å. Y II line at 3950 Å is distinctly prominent in the spectrum of HE 1015−2050. Although spectroscopically less prominent, this line is also considerably strengthened in U Aqr. Although detected clearly, there is no significant enhancement of Ba II at 4554 and 6496 Å. The atomic line of Fe I at 4045 Å is clearly detected in HE 1015−2050 as in U Aqr; however, Fe I line at 4063 Å is not clearly detected (Figure 1). Ca I line at 4226 Å, distinctly detected in HD 182040, is not

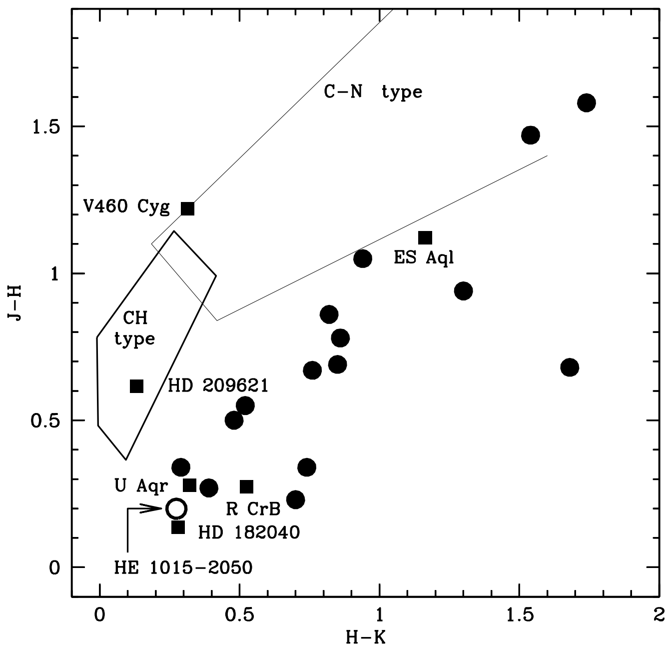

Figure 4. $J-H$ vs. $H-K$ color–magnitude diagram in which the position of HE 1015−2050 is shown by an open circle. The colors of LMC RCB stars are shown with solid circles. The positions of the comparison stars and the prototype RCB star R CrB are marked with solid squares. Most of the LMC RCB stars occupy a well-defined region as noticed in the figure. The thick box on the lower left represents the location of CH stars and the thin box on the upper right represents the location of C-N stars (Totten et al. 2000).

prominently seen in the spectra of HE 1015−2050 and U Aqr. Unlike HE 1015−2050 and U Aqr, the spectra of HD 182040 and ES Aql do not show lines of Y II at 3950 Å and Sr II at 4077 Å. The features due to Na I D, although appearing strong in HE 1015−2050 and U Aqr, are much weaker relative to their counterparts in V460 Cyg and HD 182040. The H_α feature is not detected. The most striking feature in the spectra of U Aqr and HE 1015−2050 is the strength of the Sr II λ 4215 line; this feature is inextricably blended with the nearby strong blue-degraded (0,1) CN 4216 band head in HD 182040.

3.5. Location of HE 1015−2050 in $J-H$ versus $H-K$ Plot

Apart from the spectroscopic criteria infrared colors from *JHK* photometry may be used as a supplementary diagnostic for identifying peculiar or rare stars. The Two Micron All Sky Survey (2MASS) measurements (Skrutskie et al. 2006) place the candidate cool HdC star HE 1015−2050 on the $J-H$ versus $H-K$ plane, at the bottom of the figure along with the cool LMC RCB stars and near U Aqr (Figure 4). The position of HE 1015−2050 is marked with an open circle symbol. The boxes representing the locations of CH (thick solid line box) and C-N stars (thin solid line box) are taken from Totten et al. (2000). In this figure, the locations of the cool LMC RCB stars are shown with solid circles, and the comparison stars with solid squares. The LMC photometry is taken from Alcock et al. (2001). The location of HE 1015−2050 in the vicinity of U Aqr in the $J-H$, $H-K$ plane supports its identification with the group same as that of U Aqr.

4. CONCLUDING REMARKS

Spectral analysis of 243 candidate FHLC stars of Christlieb et al. (2001) revealed one star HE 1015−2050 to be a bona-fide member of HdC stars. Its spectrum satisfies the primary spectral characteristics of HdC stars of RCB type. In particular, its spectrum closely resembles the spectrum of U Aqr, a cool Galactic HdC star of RCB type.

In the *JHK* diagram, the star occupies a position along with the cool RCB stars. This is consistent with the fact that the spectral characteristics of HE 1015−2050 do not match those of CH, C-R, CN, or C-J stars.

HdC stars and in particular RCB-type stars are a rare class of objects; only about 51 RCB stars are known in our Galaxy, about 18 in LMC, and five in SMC (Feast 1972; Alcock et al. 2001; Morgan et al. 2003; Kraemer et al. 2005; Zaniewski et al. 2005; Tisserand et al. 2004, 2008). Discovery of HE 1015−2050 adds a new member to this rare class of stars. Lawson et al. (1990) suggested that the apparent lack of cool RCBs is a selection effect, and that the true number of cool RCB stars ($\leqslant$5000 K) may greatly exceed the number of warm RCB ($\sim$7000 K) stars. The recent surveys of the LMC (Alcock et al. 2001; Morgan et al. 2003) revealed that the RCB star population is dominated by cool stars rather than warm stars by 7:2 unlike the Galaxy. The environment of LMC being more metal-poor than the solar neighborhood may also be a contributing factor. The program stars being high latitude objects, with smaller initial mass and possible lower metallicity offer potential to discover such rare objects.

The observed elemental abundances of HdC and RCB stars are similar and seem to represent the products of a combination of H- and He-burning (Warner 1967; Asplund et al. 1997, 2000; Kipper 2002). Current evolutionary models, however, cannot completely reproduce the typical RCB star abundances. None of the RCB and HdC stars are known to be binary (Clayton 1996). Abundances of Rb, Sr, Y, and Zr are greatly enhanced in U Aqr, but Ba does not show a large enhancement. Estimates of Vanture et al. 1999 ([Y/Fe] = +3.3, [Zr/Fe] = +3.0, and [Ba/Fe] = +2.1) are larger than those estimated by Bond et al. (1979), but in general agreement with those of Malaney (1985). Such abundance patterns resemble the weak component of the *s*-process found in solar system material which is best described by a single-neutron irradiation (Beer & Macklin 1989). The similarities of the spectra of U Aqr and HE 1015−2050 suggest that the HE star is also a potential candidate for studying *s*-process nucleosynthesis.

Low-mass hydrogen-deficient stars are associated with the late stage of stellar evolution. RCB phenomena characterized by spectacular dimmings of five or more magnitudes within a few days from the onset of minimum (followed by slow recovery to maximum light) are believed to be due to directed mass ejections and primarily a signature of surface activity rather than chemical peculiarity. The absence of irregular fadings may indicate the absence of such mass-ejection episodes; but whether that is the characteristic of a particular evolutionary stage is not yet established. Detailed spectroscopic as well as photometric studies are expected to provide much insight into these aspects. The spectral characteristics and its location in the $J-H$ versus $H-K$ plane certainly allow us to place HE 1015−2050 in the same group to which U Aqr belongs; however, extended photometric observations of this object would be useful to learn the nature and extent of photometric variations. In particular, it would be interesting to see if there is any sudden decline in brightness, this being a characteristic property of HdC stars of RCB type.

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