



## **Spectroscopic characterization of FHLC stars from the Hamburg/ESO survey and a newly found HdC star**

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**Abstract.** The sample of candidate faint high latitude carbon (FHLC) stars chosen from the Hamburg/ESO survey is a potential source to search for objects of rare types. From medium resolution spectral analyses of about 250 objects from this sample, the object HE 1015–2050, was found to be a hydrogen-deficient carbon (HdC) star. Apart from U Aquarii, HE 1015-2050 is the only example, till now, of a Galactic cool HdC star that is characterized by strong spectral features of light s-process element Sr, and weak features of heavy s-process elements such as Ba. This object, with its enhanced carbon and hydrogen-deficiency, together with anomalous s-process spectral features, poses a challenge as far as the understanding of its formation mechanism is concerned. We discuss possible mechanisms for its formation in the framework of existing scenarios of HdC star formation.

**Keywords :** stars: carbon - stars: Late-type - stars: HdC - stars: spectral characteristics

### **1. Introduction**

The Hamburg/ESO survey was initiated in the year 1990, for the Southern Hemisphere to complement the Hamburg/Quasar survey (HQS) that covers the Northern sky except the Galactic plane (Wisotzki et al. 1996, Reimers & Wisotzki 1997, Wisotzki et al. 2000). This survey was based on digitized objective-prism photographs taken with ESO 1m Schmidt telescope. An area of 9500 deg<sup>2</sup> in the southern sky was covered with an average limiting magnitude  $B \sim 17.5$  mag, on the prism plate. Christlieb et al. (2001) have used the Hamburg/ESO survey (HES) to augment the number of known FHLC stars. The HES spectra cover a wavelength range of 3200 -

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5200 Å and the seeing limited spectral resolution is typically 15 Å at H<sub>γ</sub>. An automated procedure based on the detection of C<sub>2</sub> and CN molecular bands of the spectra was used to identify the carbon stars. This procedure resulted 403 candidate faint high latitude carbon stars from a set of 329 plates that cover an area of 6400 deg<sup>2</sup> (87% of the survey area) to the magnitude limit V ~ 16.5. The surface density of FHLC stars ~ 0.072 ± 0.05 deg<sup>-2</sup>, is about 2-4 times higher than those obtained from previous objective prism and CCD surveys at high Galactic latitude (Sanduleak & Pesch 1988; MacAlpine & Lewis 1978, Green et al. 1994). However, it is to be noted that the majority of the carbon stars known today mostly come from the Sloan Digitized Sky Surveys (SDSS).

Although, at high Galactic latitude the surface density of FHLC stars is low, different classes of carbon stars populate the region: a) the normal AGB stars, carbon-enriched by dredge-up during the post main-sequence phase, which are found among the N-type carbon stars, b) FHLC stars showing significant proper motions and having luminosities of main-sequence dwarfs, called dwarf carbon stars (dcs) and c) the CH giants, similar to the metal-poor carbon stars found in Globular clusters and some dwarf spheroidal galaxies. Among these, warm carbon stars of C-R type are also likely to be present. The sample of stars listed by Cristlieb et al. being high latitude objects contains a mixture of these objects. Using medium resolution spectral analysis we have classified these objects based on their spectral characteristics. The spectra were obtained using the Himalayan Faint Object Spectrograph Camera (HFOSC) attached to the Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Hanle during 2005–2010. The grism and the camera combination used for observations provided a spectral resolution of ~ 1330(λ/δλ); the observed bandpass is about 3800–6800 Å. The spectra of a few objects were also acquired using the OMR spectrograph at the cassegrain focus of the 2-3-m Vainu Bappu Telescope (VBT) at Kavalur. With a 600 line mm<sup>-1</sup> grating, we get a dispersion of 2.6 Å pixel<sup>-1</sup>. The wavelength range covered is 4000–6100 Å and the resolution ~ 1000.

The membership of a star in a particular class is established from a comparison with the spectral atlas of carbon stars of Barnbaum et al. (1996). Further details on the detection procedure and the spectral characteristics of these objects are available in Goswami (2005) and Goswami et al. (2007, 2010a). In our sample of 403 stars, HE 1015–2050 is found to exhibit spectral characteristics of HdC stars. Its photometric parameters, along with those of the comparison HdC star of RCB type U Aqr are given in Table 1. HdC stars are a rare class of objects; only five non-variable HdC and fifty five RCB type stars are known so far in our Galaxy. The origin of these objects is still debated and they are poorly understood due to a lack of statistically significant sample. Each addition to this rare group of objects is therefore important.

## 2. Spectral characteristics of HdC stars

The spectra were classified using the following spectral characteristics: a) strength of band-head of the CH band around 4300 Å, b) prominence of secondary P-branch

**Table 1.** Photometric parameters of HE 1015–2050 and the comparison star U Aqr.

Star No.	$l$	$b$	B	V	B-V <sup>a</sup>	J	H	K
HE 1015-2050	261.31	29.08	16.9	16.3	0.67	14.977	14.778	14.504
HE 2200-1652 (U Aqr)	39.15	-49.81	12.1	11.1	0.99	9.562	9.283	8.961

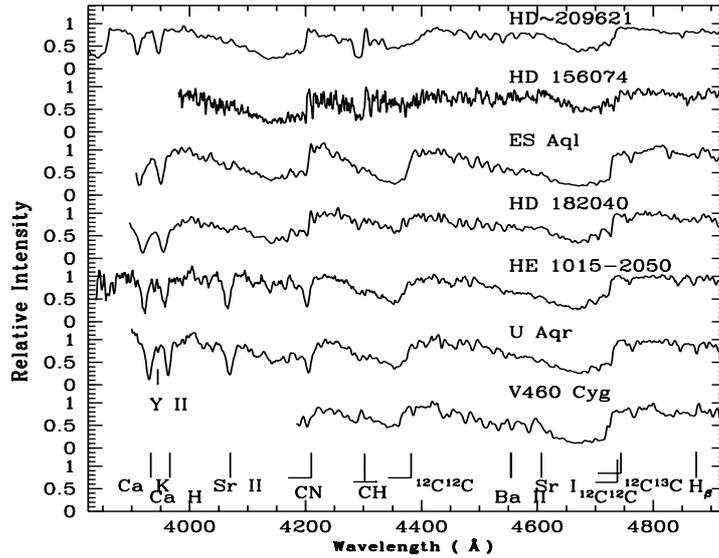
<sup>a</sup> From Christlieb et al. (2001)

head near 4342 Å, c) strength/weakness of the Ca I feature at 4226 Å, d) isotopic band strength of C<sub>2</sub> and CN, in particular the Swan bands of <sup>12</sup>C<sup>13</sup>C and <sup>13</sup>C<sup>13</sup>C near 4700 Å, e) strength of other C<sub>2</sub> bands in the 6000–6200 Å region, f) <sup>13</sup>CN band near 6360 Å and other CN bands across the wavelength range, g) strength of s-process elements such as Ba II features at 4554 and 6496 Å.

The Hydrogen-deficient supergiants comprise of three sub-classes: a) Extreme helium stars (EHes) of spectral types F and G, b) R Coronae Borealis (RCB) stars of spectral types F and G and c) hydrogen-deficient carbon (HdC) stars that are much cooler than EHes and RCBs. Similarities in chemical compositions indicate an evolutionary link between EHes and RCBs. Whether there is an evolutionary link between these stars and HdCs is not known. The abundance analysis of HdC stars is difficult because their spectra are dominated by molecular bands.

HdC stars are spectroscopically similar to the RCB stars. However, infra-red excesses and deep light minima that are characteristics of RCBs are absent in HdCs, instead they show small-amplitude light variations. Hydrogen deficiency and weaker CN bands relative to C<sub>2</sub> molecular bands are the two primary spectral characteristics of RCB stars. The strong C<sub>2</sub> molecular bands are seen in the spectra of cool RCB stars. They are weakly visible in warm RCB stars. As Balmer lines are weak in carbon stars, the strength/weakness of CH band in C-rich stars provides a measure of hydrogen deficiency. We have used hydrogen deficiency and the relative strength of C<sub>2</sub> bands in the 6000 - 6200 Å region and the CN bands near 6206 Å and 6350 Å as important classification criteria for HdC stars.

The spectrum of HE 1015-2050 is characterized by strong C<sub>2</sub> molecular bands. However, G-band (CH around 4310 Å) is only marginally detected indicating that HE 1015-2050 is a hydrogen-deficient carbon star. HE 1015–2050 bears a remarkable similarity with U Aqr, a cool RCB star. Similar to U Aqr, it exhibits an anomalously strong feature of Sr II at 4077 Å. Y II line at 3950 Å is also clearly detected in both spectra and no significant enhancement of Ba II features at 4554 Å and 6496 Å is seen. Fe I feature at 4045 Å is clearly detected. The feature due to Na I D also appears to be strong. The H<sub>α</sub> feature is not detected. The most striking feature in HE 1015–2050 and U Aqr is the Sr II at 4215 Å, this feature is blended with the nearby strong blue-degraded (0,1) CN 4216 band head in HD 182040 and ES Aql (Fig. 1).

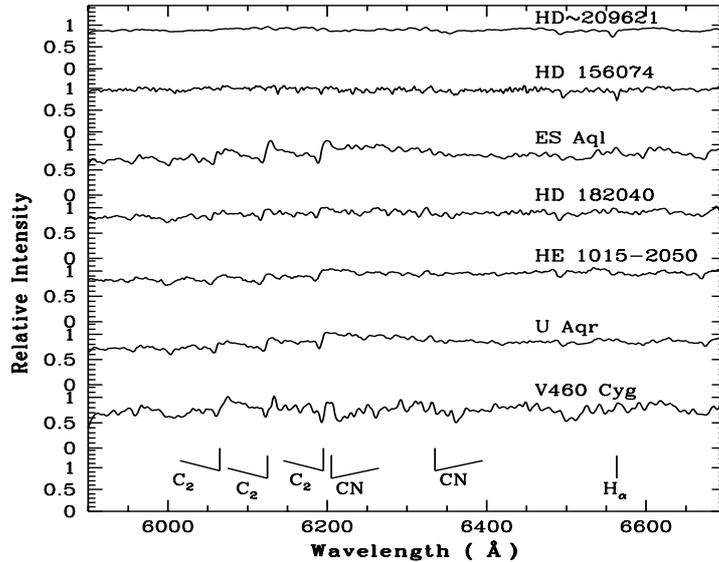


**Figure 1.** A comparison between the spectrum of HE 1015-2050 with the spectra of V460 Cyg (C-N star), U Aqr, ES Aql (cool HdC stars of RCB type), HD 182040 (a non-variable HdC star), HD 156074 (C-R star), and HD 209621 (CH star) in the wavelength region 3850-4950 Å. G-band of CH distinctly seen in the CH and C-R star's 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 prominent in the spectrum of HE 1015-2050, this line of Y II is also considerably strengthened in U Aqr. These two features of Sr II and Y II are not observed in the spectra of HD 182040 and ES Aql. The spectrum of HE 1015-2050 compares closest to the spectrum of the HdC star U Aqr of RCB type (Goswami et al. 2010b).

RCB stars are also characterized by their location in the J-H and H-K planes with respect to cool carbon stars. The Two Micron All Sky Survey (2MASS) measurements (Skrutskie et al. 2006) place HE 1015-2050 on the J-H versus H-K plane along with the cool LMC RCB stars supporting our classification.

### 3. Discussion and conclusions

The strong Sr II features observed in HE 1015-2050 are indications of enhanced s-process abundances. In late type stars such as CH giants and carbon-enhanced metal-poor objects, the observed enhanced abundances of s-process elements are generally explained on the basis of a binary picture in which the primary companion low-mass object while evolving through the Asymptotic Giant Branch (AGB) stage transfers the s-enhanced material to the secondary companion (McClure 1983, 1984; McClure &



**Figure 2.** Same as Fig. 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 is almost absent (or barely detectable) in the spectra of HE 1015-2050 and the HdC star U Aqr of RCB type.  $H_{\alpha}$  feature is distinctly seen in the spectra of the CH and C-R star HD 209621 and Hd 156074 respectively. This feature is not detectable in the spectra of HE 1015-2050 and HdC stars. Non detection of  $H_{\alpha}$ , and marginal detection of G-band of CH (Fig. 1) hints at hydrogen-poor nature of the object (Goswami et al. 2010b).

Woodsworth 1990). In case of HE 1015–2050 such an explanation is presently not applicable as its binary status is not yet known. Although none of the RCB and HdC stars known so far, are known to be binary, long-term radial velocity monitoring of HE 1015–2050 would be useful to know its binarity.

The stellar atmosphere of HE 1015–2050 has an estimated effective temperature ( $T_{eff}$ ) of 5263 K, derived using semi-empirical temperature calibration relations from Alonso et al. (1996). This temperature estimate is very similar to those of cool Galactic RCB stars such as S Aps, WX CrA, and U Aqr ( $T_{eff} \sim 5000$  K, Lawson et al. 1990). Although the resolution of our spectrum is not adequate to derive quantitative estimates one could expect this object to have similar s-elements abundance as that of U Aqr, as they exhibit very similar spectra. Vanture et al. (1999) have determined abundances of Rb, Sr, Y, and Zr in U Aqr that are found to be greatly enhanced but Ba did not show any significant enhancement. Estimates of Vanture ( $[Y/Fe] = +3.3$ ,  $[Zr/Fe] = +3.0$ , and  $[Ba/Fe] = +2.1$ ) are in general agreement with those of Malaney (1985) but larger than the estimates of Bond (1979).

The abundances of light s-process elements in solar material is attributed to ‘weak s-process’ described by a single-neutron irradiation (Beer & Macklin 1989). The main component of s-process occurs through partial mixing of protons into the radiative  $^{12}\text{C}$  layer during thermal pulses that initiate the chain of reactions  $^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta)^{13}\text{C}(\alpha, n)^{16}\text{O}$ , in a narrow mass region of the He intershell called the  $^{13}\text{C}$  pocket. The reaction  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  acts as the source of neutrons (Iben & Renzini 1982, Lattanzio 1987) in this process. The ‘weak s-process’ is assumed to occur in massive stars in He or C-burning phase. Although, no observational support exists for this scenario,  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction is believed to be the source of neutrons. This reaction has limited efficiency as most of the neutrons liberated are absorbed by light nuclei, and a few remain available for Fe-seed nuclei to capture. This process allows production of light s-process nuclei with mass numbers  $65 < A < 90$  (Prantzos et al. 1990) and Sr with mass number  $A = 87$  falls within this range. Weak s-process could therefore be a likely mechanism responsible for the observed Sr in U Aqr and HE 1015–2050.

Main-sequence objects with strong Sr are quite common but they also show equally strong Ba. However, in the globular cluster  $\omega$  Cen Stanford et al. (2006) have noted one object 2015448 with anomalously strong Sr and weak Ba. The effective temperature, surface gravity and the metallicity ( $[\text{Fe}/\text{H}]$ ) of this object are respectively 5820 K, 4.2 and  $-0.7$ . The Sr and Ba abundances with respect to Fe are respectively  $[\text{Sr}/\text{Fe}] = +1.6$  and  $[\text{Ba}/\text{Fe}] = 0.6$  (Stanford et al. 2006). A similar mechanism responsible for 2015448 formation may also hold good for HE 1015–2050 and needs further investigation. We note, however, a primary difference between 2015448 and HE 1015–2050; while the former shows carbon depletion ( $[\text{C}/\text{Fe}] = -0.5$ ), HE 1015–2050 shows enhancement of carbon.

Low mass hydrogen-deficient stars are associated with late stage of stellar evolution and are believed to be in a short-lived evolutionary phase. The characteristic light decline of five or more magnitudes shown by RCB stars within a few days from the onset of minimum (followed by slow recovery to maximum light) is suggested to be due to directed mass-ejections, which is believed to be primarily a signature of surface activity rather than chemical peculiarity. Hydrogen-deficient stars that do not exhibit such irregular fadings may indicate absence of such mass-ejection episodes; but, whether that is characteristic of a particular evolutionary stage is not yet established. Detailed spectroscopic as well as photometric studies could provide insight into these aspects. In addition, extended photometric observations of HE 1015–2050 would be useful to detect short as well as long term photometric variations observed in RCBs.

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