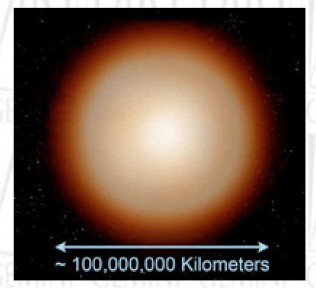
^{18}O and the Origins of Hydrogen Deficient Carbon Stars and R Coronae Borealis Stars

T. R. Geballe (Gemini Observatory), G. C. Clayton (LSU), M. Asplund (AAO), and F. Herwig and C.

Abstract: We have detected enormously enhanced abundances of ^{18}O and correspondingly small values of $^{16}O/^{18}O$ in many hydrogen-deficient carbon (HdC) stars and R Coronae Borealis (R CrB) stars, essentially all of stars of those types of stars that are cool enough to possess detectable overtone bands of CO and for which we have obtained K band spectra. In the HdC stars ^{18}O is more abundant than ^{16}O, in one case by roughly a factor of 5 ($^{16}O/^{18}O$ ~ 0.2). In R CrB stars values of $^{16}O/^{18}O$ range from 10 to near unity. The solar and interstellar values of the ratio are approximately 500. The abnormal but similar ratios suggest a common origin for the two types of stars and provides a clear way to discriminate between various scenarios . Of the two leading candidates for the origin of R CrB stars, white dwarf mergers and final helium flashes, the former appears more plausible, although further detailed modeling of the merger process and the thermonuclear reactions that occur during it are required.



INTRODUCTION

In 2004 November we discovered that in the K-band spectrum of the hydrogen-deficient carbon (HdC) star, HD 137613, the overtone (Δv=2) bands of $^{12}C^{18}O$, a normally rare isotopic species of carbon monoxide (CO), are as strong as those of the normally heavily dominant isotopomer, $^{12}C^{16}O$, indicating that the abundances of ^{18}O and ^{16}O are approximately equal in this star, an unprecedented phenomenon (Clayton et al. 2005). As strong bands of $^{12}C^{16}O$ are present in the spectrum, the finding implies a huge overabundance of ^{18}O, rather than a huge depletion of ^{16}O. A spectrum of HD 137613 obtained at UKIRT in 2005 March and shown in Fig. 1 confirmed the discovery. The solar and interstellar values of $^{16}O/^{18}O$ are ~500 and previously only two stars had been found in which the ratio is less than 100.

From a nucleosynthesis point of view the unusual O istopic signature points to partial He-burning, either in time or spatially. The latter is realized in Fig. 2. In the outer layers of the He-burning shell ^{18}O is produced via α-capture on ^{14}N nuclei which itself results from the CNO cycle H-burning ($^{14}N(\alpha,\gamma)^{18}F(\beta,\nu)^{18}O$). In these cooler, outer layers ^{18}O will not be immediately destroyed by the next α-capture, but a thin (marked) layer with a high $^{18}O/^{16}O$ layer can form. Only a bit deeper in the He-shell proper no ^{18}O can survive. Our initial interpretation of HD 137613 was that the star had somehow undergone mass loss precisely to this outer layer of the He-shell (Clayton et al. 2005).

Only five HdC stars are known (Warner 1967). As their name implies they are carbon-rich and practically devoid of hydrogen. Their photospheric temperatures range from 5000 K to 6500 K. Their elemental abundances are similar to another peculiar, but better studied and larger class of stars, the R Coronae Borealis (R CrB) stars. However, while the optical brightnesses of R CrB stars vary with time by many magnitudes in irregular fashions, none of the HdC stars are known to vary at all.

Because the above mass loss scenario appears to be highly unusual, and because it would be surprising if it occurred precisely down to the ^{18}O -enhance layer in *all* HdC stars, we asked for and received Gemini South time in semester 2005B to obtain K-band spectra of the other HdC stars and to look for the isotopomers of CO. We also were awarded time to obtain spectra of several of their cousins, the R CrB stars - those that are sufficiently cool to have detectable CO overtone bands.

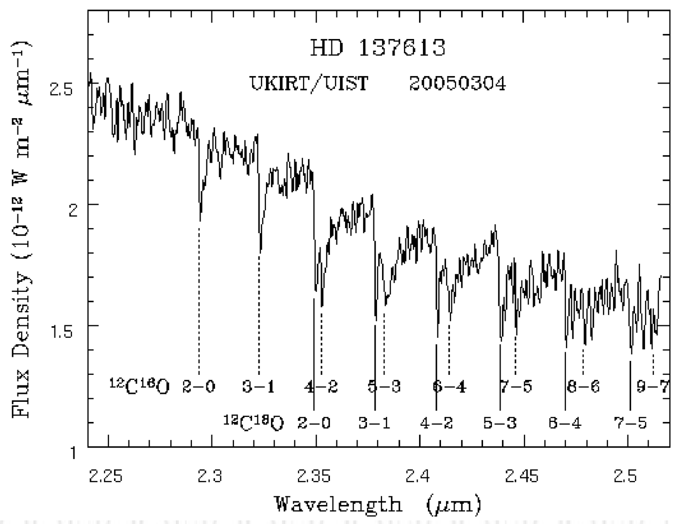


Fig. 1: 2.2-2.5µm spectrum of the HdC star HD 137613 obtained at UKIRT in 2005 March. Six overtone bands of $^{12}C^{18}O$ and eight of $^{12}C^{16}O$ are seen; the lines indicate the band heads.

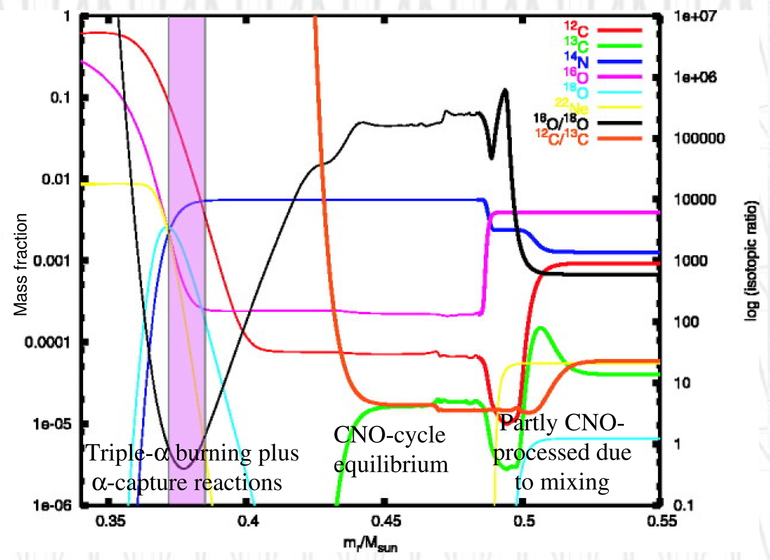


Fig. 2 Abundances and isotopic ratios of carbon, nitrogen, and oxygen in the He and H shells of a $2M_{sun}$, Z= 0.01 stellar evolution model during the E-AGB, soon after the end of He-core burning. The red-shaded band indicates the region in which $^{16}O/^{18}O$ < 1. The temperature rises from the right to left (from the outside to the interior).

OBSERVATIONS AND RESULTS

Spectra in the long wavelength half of the K window were obtained in 2005 September with GNIRS, using its 110 l/mm grating and 0.3" slit, which yield a resolving power of ~5900. Data were reduced using standard IRAF and FIGARO routines.

The reduced spectra are shown in Fig. 3. All data are from Gemini South except for HD 137613 (UKIRT) and Z UMi (Steward). Lines of CN contaminate the entire spectral region, but the bands of CO can be easily seen in most stars. To summarize:

1. Four of the five HdC stars have bands of $^{12}C^{18}O$ that are as strong or stronger than those of $^{12}C^{16}O$. We originally claimed to clearly detect $^{12}C^{18}O$ in only three HdC stars HD 137613, HD182040, and HD 175843. However, $^{12}C^{18}O$ lines have now been detected in HD 148839 using Phoenix at Gemini South (K. Hinkle, private communication), and weak bands are also present in the GNIRS spectrum (see Fig. 3). The fifth HdC star, HD 173409, is too hot to have detectable CO.
2. All of the R CrB stars have detectable bands of $^{12}C^{16}O$ and $^{12}C^{16}O$. Except for WX CrA, the bands of $^{12}C^{18}O$ are weaker than those of $^{12}C^{16}O$.
3. No bands of other CO isotopomers are detected.

Every HdC and R CrB star cool enough to have detectable CO has unusually strong bands of $^{12}C^{18}O$, with ^{18}O more extremely enhanced relative to ^{16}O in HdC stars than in R CrB stars.

REFERENCES

Clayton, G.C., Herwig, F., Geballe, T.R., Tenenbaum, E.D., Engelbracht, C.W., & Gordon, K.D. 2005 ApJ, 623, L141
Clayton, G.C, Geballe, T.R., Herwig, F., Fryer, C., & Asplund, M. 2007, ApJ, 662, 1220
Iben, I.J., Tutokkov, A.V., & Yungelson, L.R. 1996, ApJ, 456, 750
Saio, H. & Jeffery, C.S. 2002, MNRAS, 333, 121
Warner, B. 1967, MNRAS, 137, 119
Webbink, R.F. 1984, ApJ, 277, 355

GEMINI SOUTH - GNIRS SPECTRA

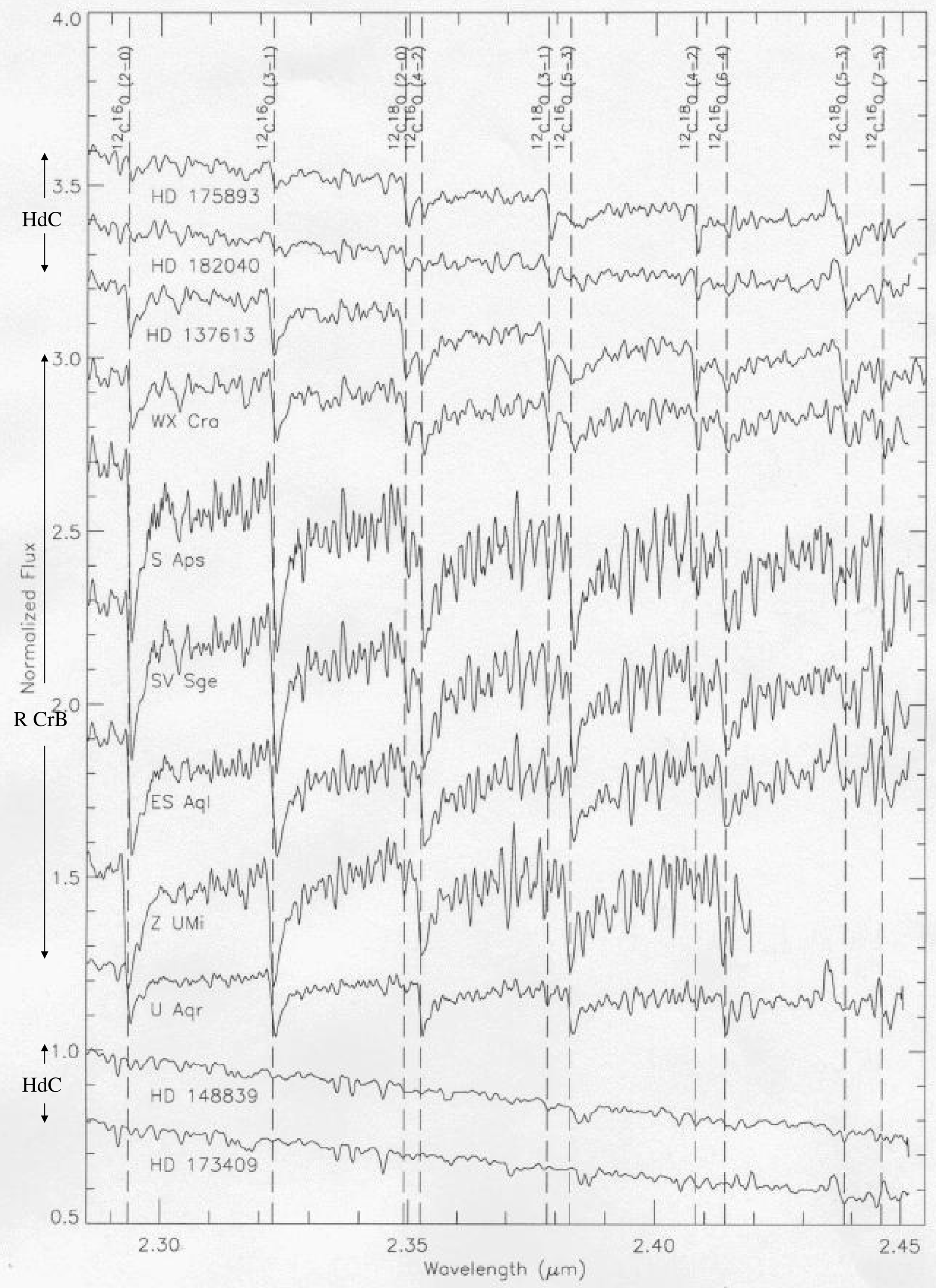


Fig. 3 Spectra of HdC and R CrB stars. All but those of HD 137613 and Z Umi were obtained at Gemini South during Semester 2005B. The wavelengths of $^{12}C^{16}O$ and $^{12}C^{16}O$ band heads are indicated by dashed lines.

ANALYSIS OF SPECTRA

Synthetic spectra for T = 5000, 5500, and 6000 K photospheres, with typical carbon star abundances and with $^{16}O/^{18}O$ = ∞, 10, 3, 1, 0.33, and 0.1, based on MARCS model atmospheres, were generated and compared with the observed spectra. Equivalent widths of observed and modeled CO bands were compared and interpolated to produce the estimated ratios of band strengths and isotopic ratios given in the table below (from Clayton et al. 2007).

Table 2. Estimated Isotopic Oxygen Abundances

Star	HdC/RCB	T_{eff}	abs($C^{16}O$)/abs($C^{18}O$)	$^{16}O/^{18}O^a$
HD 175893	HdC	5500	0.4	0.2
HD 182040	HdC	5600	0.6	0.3
HD137613	HdC	5400	0.7	0.5
WX CrA	RCB	5300	1.3	1
S Aps	RCB	5400	2.5	4
SV Sge	RCB	4000	2.5	4
ES Aql	RCB	5000	3	6
Z UMi	RCB	5000	≥4	≥8
U Aqr	RCB	6000	≥6	≥12
HD 148839	HdC	6500	0.7	0.5
HD 173409	HdC	6100	…	…

[a] Estimated uncertainty is a factor of two.

References. — Asplund et al. (1997); Lawson et al. (1990); Bergeat et al. (2001)

FORMATION THEORIES FOR R CrB and HdC STARS

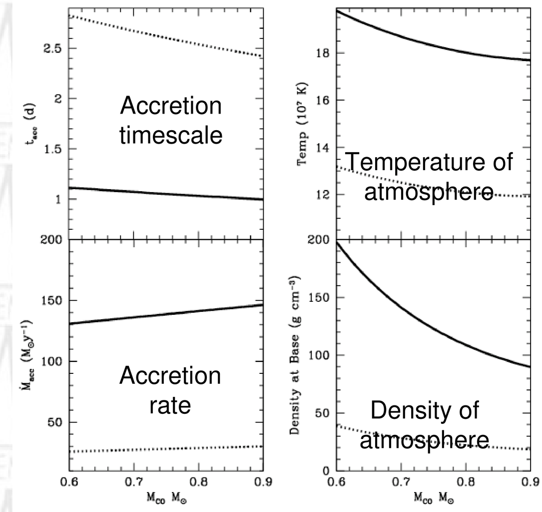
The spectacular high abundances of ^{18}O revealed in these spectra imply a close relationship between R CrB and HdC stars; the two classes of stars must have similar evolutionary paths. Little is known about the origins of HdC stars, but the origins of the R CrB stars have been the subject of considerable research. The two leading candidates are (1) the merger of a helium white dwarf (He-WD) and a carbon/oxygen white dwarf (C/O-WD) (Webbink 1984), and (2) the final He flash (FF) of an incipient WD (Iben et al. 1996).

The FF hypothesis appears to fail on at least two fronts. First, recent observations of FF events suggest that after the FF the star spends too short an amount of time in the temperature-luminosity regime occupied by R CrB stars to account for the number of R CrB stars in the Galaxy. Second, the isotopic ratios of oxygen and carbon observed in the few known FF events and predicted theoretically do not match those observed in R CrB and HdC stars (low **$^{16}O/^{18}O$, high $^{12}C/^{13}C$).**

Fig. 4: Accretion parameters

Solid lines: $0.4M_{Sun}$ He-WD,
Dotted lines: 0.2 M_{Sun} He-WD
X-axis: Mass of C/O WD

Timescales (days) are much shorter than estimated earlier by Saio & Jeffery (2002).



INITIAL MODELING OF MERGER AND NUCLEOSYNTHESIS

A majority of binaries that are close enough to interact sometime during their evolution will end up as doubly degenerate systems where both stars become WDs. The evolution will result in two mass transfer phases, including at least one common envelope phase when the first star to become a WD is engulfed by the other. The WD pair may merge due to the loss of energy to gravitational radiation if the binary has a period less than about 0.2 hr. Such a merger can have a variety of results (including an SN Ia explosion), depending on the total and relative masses. Here we consider the merger of a C/O-WD of mass 0.6-$0.9M_\odot$ and a He-WD of mass 0.2-$0.4M_\odot$, in which the He-WD is disrupted and partially accreted onto the C/O-WD with resultant He-burning on the surface of the C/O-WD, with remainder of the disrupted He-WD forming the envelope of the R CrB or HdC star, according to Webbink (1984).

Our initial calculations indicate that the merger takes only a few days and produces temperatures of 1-2 x 10^8 K at the base of the accreted envelope (see Fig. 4). If that time scale and temperature regime are both correct then partial He-burning occurs only over a short time interval, and it is plausible that the merger provides conditions for the α-capture reaction to produce a significant amount of ^{18}O and not destroy it shortly afterwards (see Fig. 5). Our model also provides qualitative agreement with observed values of $^{12}C/^{13}C$ and CNO elemental abundances. Possible problems are (1) under some circumstances $^{16}O/^{18}O$ can attain values much less than or much greater than those observed, dependent on temperature, density, and duration of the He-burning, and (2) our simple model does not account for s-process element enhancements observed in R CrB stars. However, admixture of hydrogen during the accretion process from the small H-rich outer portion of the C/O-WD envelope may play an important role in producing the observed abundances. Overall, our analysis shows that WD mergers are viable as progenitors of the R CrB and HdC stars, and that more detailed modeling of the mergers is justified.

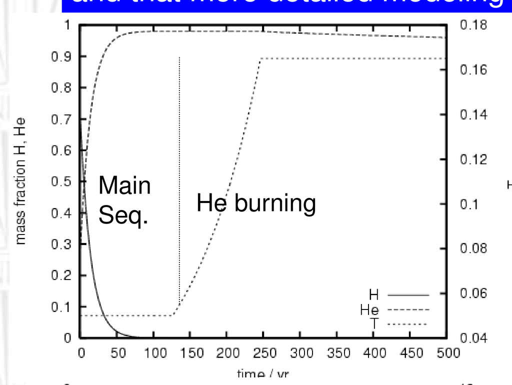


Fig. 5: Parametric Model of Nucleosynthesis
One-zone nucleosynthesis model of the conditions during the merger
- Simulate H-burning
- Temp increase 1%/yr to get He-burning
- Stop increase at 1.65 x 10^8 K - takes 125 years (for higher T the N and He abundances are reduced below those observed in R CrB and HdC stars)
- Allow network to continue for 250 years (until abundances are inconsistent with observations)

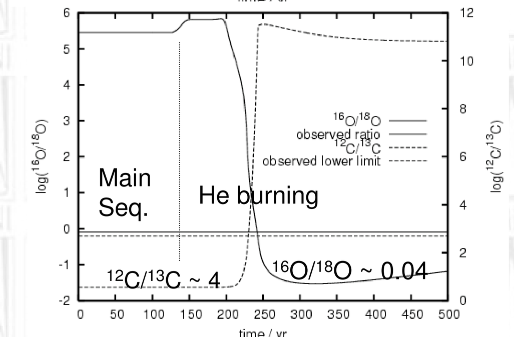


Fig. 6: $^{16}O/^{18}O$ and $^{12}C/^{13}C$

rapid decrease in $^{16}O/^{18}O$ due to $^{14}N(\alpha,\gamma)^{18}F(\beta,n)^{18}O$ and rapid increase of $^{12}C/^{13}C$ due to triple- α

($^{13}C(a,n)^{16}O$ plays a small role at start of He-burning)

GEMINI OBSERVATORY

We thank the staff of Gemini for its support of our observations. The Gemini Observatory is operated by the Association of Universities for Research in Astronomy on behalf of in international Gemini partnership of Argentina, Australia, Brazil, Canada, Chile, the United Kingdom, and the United States of America.