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An Extremely Large Excess of ^{18}O in the Hydrogen-Deficient Carbon Star, HD 137613

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ABSTRACT

We report the discovery of a uniquely large excess of ^{18}O in the hydrogen-deficient carbon (HdC) star, HD 137613, based on a spectrum of the first overtone bands of CO at 2.3-2.4 μm in which three strong absorption bands of ^{12}C^{18}O are clearly present. Bands of ^{12}C^{16}O also are present but no bands of ^{13}C^{16}O or ^{12}C^{17}O are seen. We estimate an isotopic ratio ^{16}O/^{18}O $\lesssim 1$. The Solar value of this ratio is $\sim$500. Neither He-core burning nor He-shell flash burning can produce the isotopic ratios of oxygen and carbon observed in HD 137613. However, a remarkable similarity exists between the observed abundances and those found in the outer layers of the broad He-shell of early-AGB stars, soon after the end of He-core burning. It is not known how the outer envelope down to the He-shell could be lost but some mechanism of enhanced mass loss must be involved. HD 137613 may be a post-early-AGB star with the outer layers of the former He-burning shell as its photosphere. The unusual elemental abundances of the HdC stars resemble those of the R Coronae Borealis (RCB) stars, but HdC stars do not produce clouds of dust that produce declines in brightness. None of the other RCB or HdC stars observed shows significant ^{18}O.

Subject headings: stars: evolution, stars: post-AGB, stars: carbon

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1. Introduction

Hydrogen-deficient post-asymptotic giant branch (post-AGB) stars are very rare. Among them are the R Coronae Borealis (RCB) stars, a small group of carbon-rich supergiants. About 50 RCB stars are known in the Galaxy and the Magellanic Clouds (Clayton 1996; Alcock et al. 2001; Tisserand et al. 2004). A defining characteristic of RCB stars is their unusual variability - RCB stars undergo massive declines of up to 8 magnitudes due to the formation of carbon dust at irregular intervals.

In addition to the RCB stars, five hydrogen-deficient carbon (HdC) stars are known. The HdC stars are similar to the RCB stars spectroscopically but do not show declines or IR excesses (Warner 1967; Feast & Glass 1973; Feast et al. 1997). The paucity of HdC stars is no doubt due to the difficulty of recognizing these stars without the large variability which causes the RCB stars to stand out. Taking this into account, there may be up to 1000 HdC stars in the Galaxy (Warner 1967). The RCB and HdC stars all have similar abundances indicating that they may be related objects (Lambert & Rao 1994). None of the HdC or RCB stars is known to be a binary (Clayton 1996).

Understanding the RCB and HdC stars is a key test for any theory that aims to explain hydrogen deficiency in post-AGB stars. Two models have been proposed for the origin of the RCB stars: the double degenerate and the final helium-shell flash (Iben, Tutukov, & Yungelson 1996; Saio & Jeffery 2002). The former involves the merger of two white dwarfs, and in the latter, a white dwarf/evolved planetary nebula (PN) central star is blown up to supergiant size by a final helium flash. The final-flash model implies a close relationship between RCB stars and PNs. This connection has recently become stronger, since the central stars of three old PNs (Sakurai's Object, V605 Aql, and FG Sge) have been observed to undergo final-flash outbursts that transformed them from hot evolved central stars into cool giants with the spectral properties of RCB stars (Kerber et al. 1999; Asplund et al. 1999; Clayton & De Marco 1997; Gonzalez et al. 1998). Two of these stars, FG Sge and Sakurai's object, have recently undergone RCB-like brightness variations.

Warner (1967) conducted the only major abundance analysis to date of the five known HdC stars. He predicted that nearly all of the O in HdC stars would be in ^{18}O and suggested a search for it in the infrared bands of CO. Lambert (1986) detected the CO absorption bands near 2.3 μm in the HdC star HD 182040, but did not detect ^{12}C^{18}O, indicating that the ^{16}O/^{18}O ratio is probably large . A R$\sim$900 spectrum of the HdC star HD 137613, showing the first overtone ^{12}C^{16}O CO bands is given in Eyres et al. (1998). At their resolving power, the ^{12}C^{16}O and ^{12}C^{18}O bandheads would not be resolved. Eyres et al. comment that the ^{12}C^{16}O 2-0 and 3-1 bands are oddly weaker than bands from higher vibrational levels. In this paper, we report new higher resolution observations of the first overtone CO bands near

2.3 μm in HD 137613.

2. Observations and Results

Near-IR spectra were obtained of the HdC star, HD 137613, in 2000 June. The spectra were obtained at the Steward Observatory's 90-inch Bok telescope at Kitt Peak, Arizona, with FSpec, a cryogenic long-slit near-IR spectrometer utilizing a NICMOS3 256 x 256 array (Williams et al. 1993). A 600 lines mm^{-1} grating was used, giving a resolving power of ∼3000. Wavelength calibration was achieved by using features from arcs, telluric absorption features, and OH lines from the night sky. The observations were reduced by dividing the spectrum by that of a nearby comparison star to remove the instrumental response and the effects of atmospheric absorption. The long wavelength portion of the K-band spectrum of HD 137613 is shown in Fig. 1. The spectrum has been shifted to compensate for the measured radial velocity of the star (Lawson & Cottrell 1997). The bandheads of various isotopes of CO are listed in Table 1 and indicated in Fig 1. The signal-to-noise ratio of the spectrum is ∼50-80 over the range, 2.28-2.34 μm, and ∼30-50 in the range 2.34-2.42 μm.

The most remarkable feature of the figure is the presence in HD 137613 of three strong absorption bands of $^{12}C^{18}O$, readily identified by their bandheads at 2.349 μm (2-0 band), 2.378 μm (3-1), and 2.408 μm (4-2), in addition to the strong and commonly observed bands of $^{12}C^{16}O$. The $^{12}C^{18}O$ bandheads closely match the calculated wavelengths, to the same precision as do the $^{12}C^{16}O$ bandheads. The spectrum in Fig. 1 shows no evidence for bands of $^{13}C^{16}O$, which are present in the spectra of some carbon stars. As illustrated in Table 1 the bandheads of $^{12}C^{17}O$ lie too close to those of $^{12}C^{16}O$ to be investigated at this resolution. One can only conclude from the similar strengths of the isolated $^{12}C^{16}O$ 2-0 band and the other $^{12}C^{16}O$ bands that $^{12}C^{16}O$ is much more abundant than $^{12}C^{17}O$. The spectra of eight RCB stars and one other HdC star, HD 182040 were also examined for evidence of significant $^{12}C^{18}O$ absorption bands (Tenenbaum et al. 2005). None were found.

There are numerous other features in the spectrum of HD 137613. Several groups (e.g., Wallace 1997 & Hinkle 1997; Forster Schreiber 2000; Bieging, Rieke & Rieke 2002) have presented spectra of carbon stars in this spectral interval. Many of their spectra, as do ours, show spectral structures that are not due to CO. Bieging et al. point out that the rich organic chemistry in cool carbon star atmospheres leads to presence of significant amounts of many carbon compounds. Although it is remotely possible that other spectral features can account for the spectral structures at 2.349 μm (2-0 band), 2.378 μm (3-1), and 2.408 μm (4-2) in HD 137613, the wavelength matches, the similar strengths of the three features, and the characteristic asymmetric profiles (especially of the two longer wavelength features that are further separated from the nearby $^{12}C^{16}O$ bandheads), argue strongly for their identification as $^{12}C^{18}O$.

3. Analysis of $^{16}O/^{18}O$ in HD 137613

Each of the $^{12}C^{18}O$ bandheads in HD 137613 lies just shortward of a $^{12}C^{16}O$ bandhead whose vibrational quanta are higher by 2, with the spectral separation of the feature pairs increasing towards longer wavelengths. The pairs of bandheads are of roughly similar strength in HD 137613. The bands have closely similar energy levels, and lines of the species have similar transition rates and thus the roughly similar strengths suggest similar abundances. However, the $^{12}C^{16}O$ bandheads lie within the band structures of $^{12}C^{18}O$, and thus are probably intrinsically slightly weaker than the $^{12}C^{18}O$ bandheads. This in itself suggests that $^{12}C^{18}O$ may be slightly more abundant than $^{12}C^{16}O$.

One measure of the relative abundances of $^{12}C^{16}O$ and $^{12}C^{18}O$ is to compare the equivalent widths of identical portions of the *same* bands of the isotopomers. Using 0.002 μm-wide regions centered on the deepest portions of the 2-0 and 3-1 bands, close to the heads we derive 0.83 +/- 0.02 for the ratio of the equivalent widths. Uncertainties in the continuum level and in the different degrees of contamination by other molecular species and uncancelled telluric features of each spectral region are much larger than the above uncertainty. However, the similar results obtained for the 2-0 and 3-1 bandheads of $^{12}C^{16}O$ and $^{12}C^{18}O$ indicate that an isotopic ratio less than unity is likely. The effects of saturation are also uncertain, but would most likely be somewhat greater in the species with the larger equivalent width, $^{12}C^{18}O$. We tentatively conclude from this test that $^{16}O/^{18}O$ is $\lesssim$ 0.8 in HD 137613.

To confirm the identification of the $^{12}C^{18}O$ bands and the relative abundance of $^{16}O/^{18}O$, we have computed sample MARCS model atmosphere flux distributions with opacity sampling for different CO isotopic abundances (Asplund et al. 1997a; Gustafsson et al., in preparation). We have adopted the stellar parameters $T_{\rm eff} = 5500\,{\rm K}$ and $\log g = 1.5$ [cgs] and a chemical composition typical of RCB stars (Asplund et al. 1997a). Asplund et al. also estimate the $T_{\rm eff}$ of HD 137613 to be $\sim$5400 K. We emphasize that the particular values are not crucial for the results on the O isotopic ratio. We ran models with $^{16}O/^{18}O$=1 and with ^{18}O=0. These models are plotted in Figure 1 for comparison with HD 137613. The CO isotopic line list used stems from Goorvitch (1994). These calculations strengthen the conclusion that $^{12}C^{18}O$ absorption bands are indeed present. Given the preliminary nature of these computations, we have not attempted a perfect fit but the exercise suggests that $^{16}O/^{18}O \lesssim 1$, in line with the above estimates. Indeed, the relatively low resolving power and S/N do not warrant a detailed spectrum synthesis analysis. We intend to return to this issue with proper spectrum synthesis using improved observations of HD 137613 (and other HdC stars) with higher resolving powers and signal-to-noise ratios.

4. Discussion

The value of the isotopic ratio ^{16}O/^{18}O is ∼500 in the solar neighborhood (Geiss, Gloeckler, & Charbonnel 2002) and varies from 200 to 600 in the Galactic interstellar medium (Wilson & Rood 1994). The presence of large amounts of ^{18}O in a stellar atmosphere is unusual to say the least. One other star, the post-AGB star HR 4049, has been found to have highly enhanced ^{18}O (and ^{17}O; Cami & Yamamura 2001). However, relative to ^{16}O, ^{18}O is an order of magnitude more enhanced in HD 137613. HR 4049 is a binary and its enhanced oxygen isotopes are found in the circumbinary disk material. HR 4049 is not hydrogen deficient (e.g., Bakker et al. 1996). No RCB or HdC star is known to be a binary. High abundances of ^{18}O have also been measured in pre-solar graphite grains in the Murchison meteorite (Amari, Zinner, & Lewis 1995). These ^{18}O anomalies are attributed to material processed in massive Wolf-Rayet stars. In the meteoritic material, large abundances of ^{18}O are correlated with large abundances of ^{13}C also which is the opposite of what is seen for HD 137613.

The elemental abundances of the HdC stars are similar to those of the majority of RCB stars (Warner 1967; Asplund et al. 1997a; Kipper 2002). The typical RCB abundances are characterized by extreme hydrogen deficiency, enrichment relative to Fe, of N, Al, Na, Si, S, Ni, the s-process elements and sometimes O (Asplund et al. 2000). The isotopic carbon ratio, ^{12}C/^{13}C is always very large. Li is seen in four of the RCB stars and at least one HdC star, HD 148839 (Rao & Lambert 1996). Also, the C/He ratio is high. These abundances seem to indicate that a combination of H- and He-burning products are present in the observed atmospheres of the HdC and RCB stars. A hydrogen-deficient post-AGB star can be produced with a late thermal pulse or helium-shell flash where the outer H envelope is fully ingested and burned into He (Herwig et al. 1999). The agreement of this evolution scenario with some RCB-like stars, like Sakurai's object is in fact quite promising. However, current evolution models cannot reproduce the typical RCB star abundances.

Model atmosphere fitting, using similar models to Asplund et al. (2000), has been applied to the visible spectrum of HD 137613 (Kipper 2002). It was found that T_{eff}=6000±200 K. HD 137613 is extremely hydrogen deficient by a factor of $\sim 10^5$ compared to the Sun. Its spectrum does not show any Li λ6707 (Vanture, Zucker, & Wallerstein 1999; Kipper 2002). In general, the abundances of HD 137613 agree with the majority of RCB stars (Asplund et al. 2000). The visible spectrum of HD 137613 resembles a typical cool, T_{eff} <6000 K RCB star with strong bands of CN and C_2 (Lloyd Evans, Kilkenny, & van Wyk 1991). It shows no sign of ^{13}C in the visible.

While RCB stars and HdC stars are not well understood in general, HD 137613 must be regarded as a particularly remarkable case because of its strikingly low ^{16}O/^{18}O ratio. In the context of low- or intermediate mass stellar evolution ^{18}O is affected both by H-burning and He-burning. Starting from a solar value of $\sim$ 500 this ratio may in fact increase somewhat in the envelope of low mass stars during the post-main sequence evolution as the star evolves up the first giant branch (Stoesz & Herwig, 2003). This modification is the result of convective envelope mixing that engulfs partially CNO-cycled matter. In general, the proton capture rates of ^{18}O are much larger than the $^{16}\mathrm{O}(p,\gamma)^{17}F$ reaction. For example, for $T = 3 \cdot 10^7$K the ratio of the $^{18}\mathrm{O}(p,\alpha)$ and the $^{16}\mathrm{O}(p,\gamma)$ rate is 4000 (Angulo et al. 1999). Accordingly, any nucleosynthesis site that involves efficient hydrogen burning can be excluded as the origin of the peculiar abundances of HD 137613. This is consistent with the high observed ^{12}C/^{13}C ratio of $\sim$ 500 in HD 137613 (Fujita & Tsuji 1977). The equilibrium isotopic ratio of carbon in CNO burning is 3.5. In Sakurai's object, the ^{12}C/^{13}C ratio is about 4 (Asplund et al. 1997b, Pavlenko et al. 2004), consistent with hot proton-limited burning predictions in the context of the very late thermal pulse that causes a born-again evolution. Moreover, Sakurai's Object has shown no indication of enhanced 18O (Eyres et al. 1998). Thus, Sakurai's Object and HD 137613 have very different carbon and oxygen isotopic ratios.

The ^{18}O also can be produced by α-capture reactions. In the H-burning ashes almost all CNO isotopes have been transformed into ^{14}N. Then, as the temperature and density increase the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+\nu)^{18}\mathrm{O}$ reaction will be activated. For example, at the onset of He-core burning in a 2M$_\odot$ star the lifetime of ^{14}N against α-capture is 10 million years (at $T = 10^8$K and $\rho = 10^5$g/cm^3). Indeed, He-core burning models initially show a sharp drop in the ^{16}O/^{18}O ratio. The lowest value in a 2M$_\odot$ model is 4, obtained when only a few percent of the initial core ^{14}N abundance is burned. At this time, for an initial metallicity of $Z = 0.01$, the central ^{16}O mass fraction is $5 \cdot 10^{-4}$. Soon thereafter the triple-α reaction produces enough ^{12}C so that ^{16}O is made from $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$. The result is a quickly increasing ^{16}O/^{18}O ratio. By the time half of the ^{14}N is gone, the ratio is 30 in the center. the ^{18}O is now being removed via $^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$, leading to a continuously rising ^{16}O/^{18}O ratio in the center. At the end of He-core burning all ^{18}O is destroyed. Thus, complete He-burning, as it occurs in the cores of low mass stars cannot account for the observed oxygen isotopic ratio either.

It is equally impossible to generate small ^{16}O/^{18}O ratios in the He-shell flash episodes of evolved AGB stars. The typical temperatures at the bottom of the He-shell flash convection zones is $2.5 \cdot 10^8$K and the density is 1500 gcm^{-3}. In these conditions the lifetime of ^{18}O against α-capture is only a few days, but the high-temperature conditions may last for much longer, typically one year. Thus, all ^{14}N is transformed into ^{22}Ne and the ^{16}O/^{18}O ratio in the He-shell flash is high (depending on the exact conditions, 50 to several hundred). While the ^{13}C abundance is very low and ^{12}C is high, this environment cannot provide the observed slightly depleted ^{16}O and significantly enhanced ^{14}N.

While neither He-core burning nor He-shell flash burning can produce the observed abundance pattern, there is a remarkable similarity between the observed abundances and those present in the outer layers of the broad He-shell of early-AGB (E-AGB) stars, soon after the end of He-core burning. A profile for such a situation is shown in Fig. 2 (Herwig & Austin 2004). The inner radius of the H-shell is located at mass coordinate $0.5 M_{\odot}$. The layer below this, down to $0.4 M_{\odot}$, is unprocessed H-shell ash material, characterized by the large ^{14}N abundance. The red region marks the region in which all of the observed CNO abundance characteristics of HD 137613, including ^{16}O/^{18}O, can be reproduced. This region is characterized by partial He-shell burning in the outer cooler layers of the shell. The ^{14}N starts to be depleted and ^{22}Ne appears. The intermediate product ^{18}O has a peak. It is this peak that leads to the low ^{16}O/^{18}O ratio, at a location where He-burning is not yet efficient enough to make significant amounts of ^{16}O. In fact, in this region the ^{16}O is just below the initial abundance (seen at the very right end of the figure), which is just what is observed. The region can also accommodate enhanced ^{14}N and ^{12}C abundances, and even the relative C and N overabundances are qualitatively reproduced. This region does not contain ^{13}C.

The outer layer of the He-shell, shortly after the end of He-core burning and before the start of thermal pulses later on the AGB, is a robust feature of low-mass models. However, this layer is buried in the stellar interior, below the H-shell. While other scenarios can be invented to explain the observed pattern, we think that this particular location in terms of the nucleosynthesis most naturally corresponds to the observations. It is not clear, however, how the mass all the way down to the He-shell can be lost. It seems that some mechanism of enhanced mass loss must be involved. However, the transition of stars of about a solar mass from the AGB to the post-AGB has not been studied in detail yet. During this particular phase of E-AGB evolution most of the luminosity is generated by the He-shell. If the star has already lost mass during the RGB evolution it may arrive at the E-AGB with an envelope mass so small that it never reaches the first thermal pulse. Instead such a star would evolve off the E-AGB, and because the H-shell is not active, mass loss may proceed to peel off layers of H-burning ashes. This scenario is consistent with the observed abundances of HD 137613 but more elaborate models will be necessary to match them in detail and to answer questions such as how and where the neutrons are produced. We speculate at this point that HD 137613 is, in fact, a post-E-AGB star, and that it shows on its surface the outer layers of the former He-burning shell. Further observations are planned to obtain higher quality spectra for detailed model analysis (e.g., Asplund et al. 2000).

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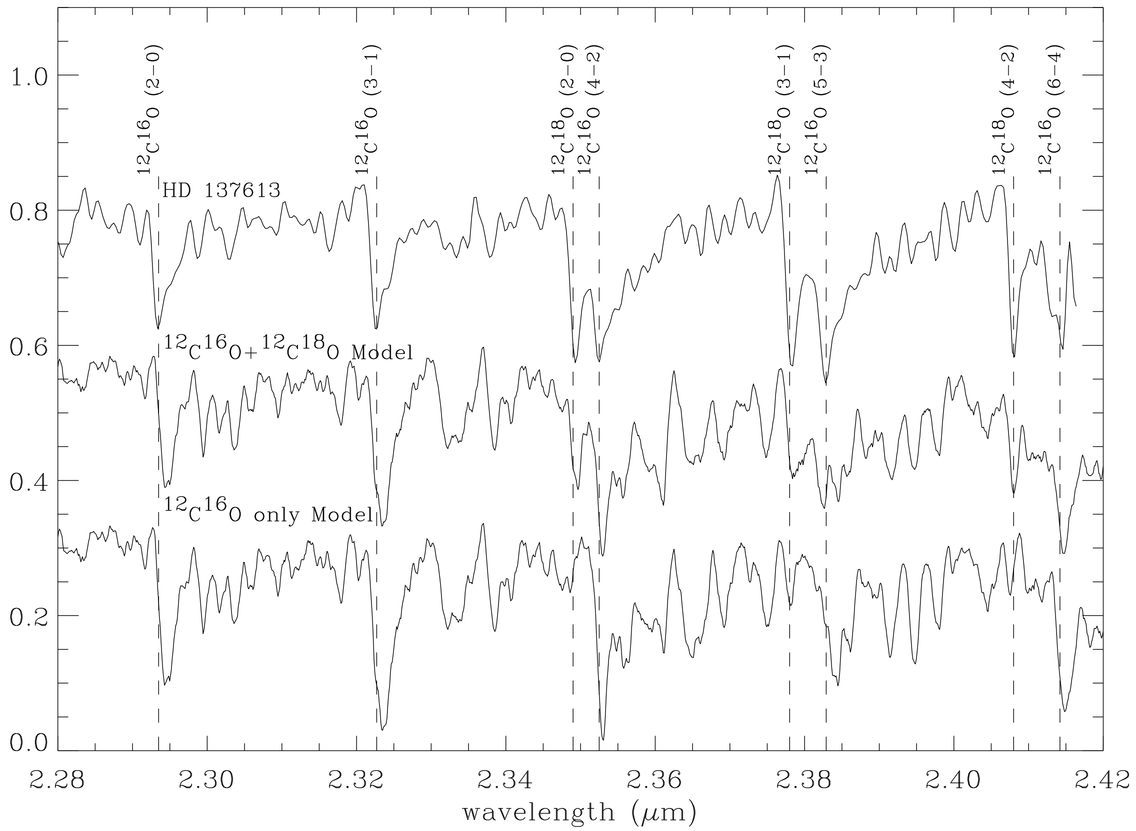

Fig. 1.— K-band spectrum of the HdC star, HD 137613, and two MARCS model atmosphere flux distributions with opacity sampling for different CO isotopic abundances ($^{16}O/^{18}O=1$ and $^{18}O=0$). We have adopted the stellar parameters $T_{\rm eff}$ = 5500 K and $\log g$ = 1.5 [cgs] and a chemical composition typical of RCB stars. The spectra were normalized and have been shifted vertically for the purposes of plotting. RMS noise is typically 0.01–0.02 of the continuum for HD 137613. The tickmarks show the locations of the bandheads of $^{12}C^{16}O$ and $^{12}C^{18}O$.

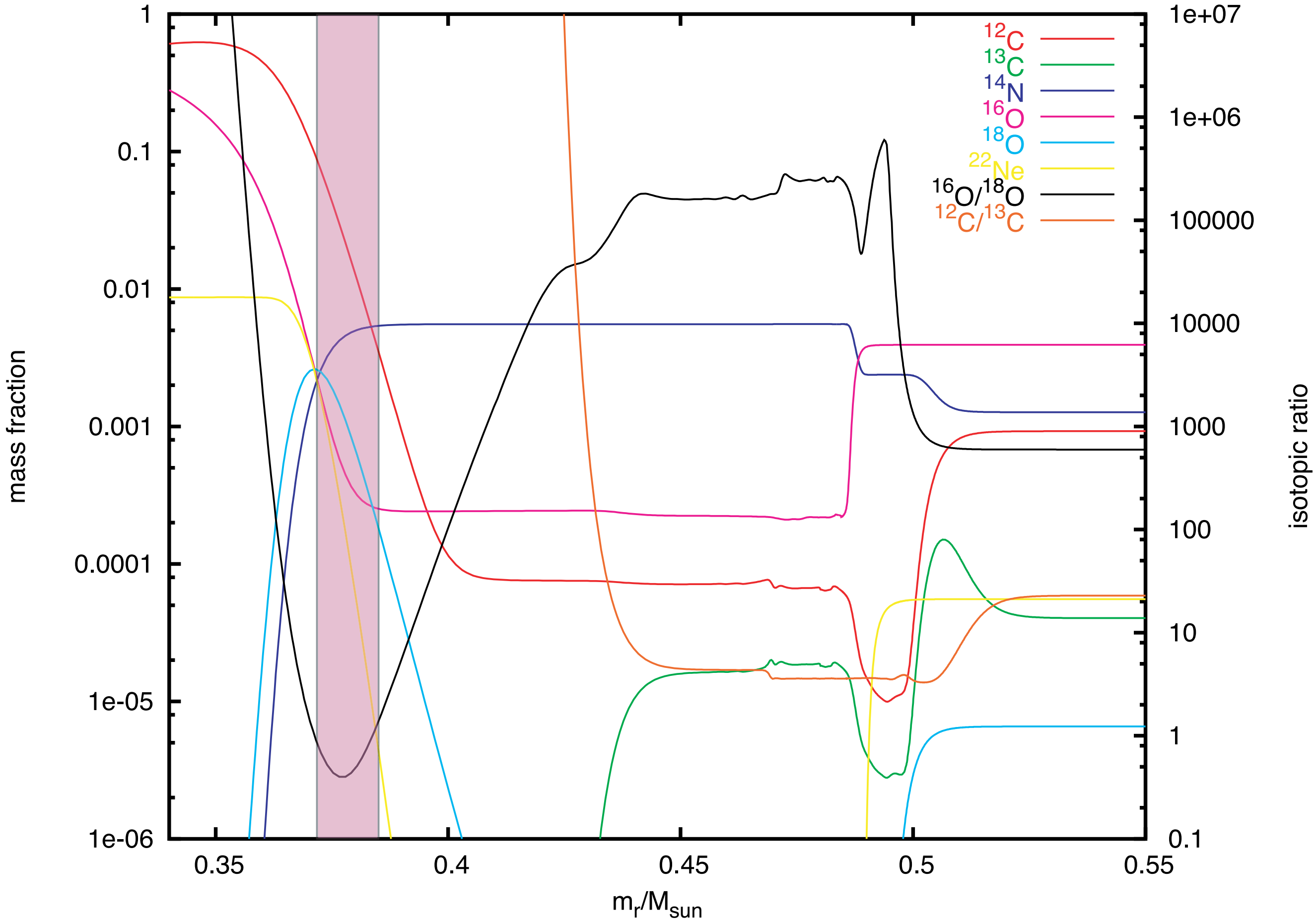

Fig. 2.— Abundances and isotopic ratios of carbon and oxygen in the He- and H-shell of a $2M_{\odot}$, $Z = 0.01$ stellar evolution model during the E-AGB, soon after the end of He-core burning. The red shaded band indicates the region of the profile in which $^{16}O/^{18}O < 1$. The temperature rises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

Table 1. Bandhead Wavelengths (vacuum μm)[a]

Species	2–0	3–1	4–2	5–3	6–4
$^{12}C^{16}O$	2.2935	2.3227	2.3525	2.3829	2.4141
$^{12}C^{18}O$	2.3492	2.3783	2.4081	2.4385	
$^{12}C^{17}O$	2.3226	2.3517	2.3815	2.4119	
$^{13}C^{16}O$	2.3448	2.3739	2.4037	2.4341	

[a] Calculated from molecular constants in Mantz et al. (1975)