THE ASTROPHYSICAL JOURNAL, 292:620–627, 1985 May 15

OXYGEN ISOTOPIC ABUNDANCES IN EVOLVED STARS. I. SIX BARIUM STARS

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Received 1984 September 17; accepted 1984 November 20

ABSTRACT

Oxygen isotope ratios have been measured in four Ba II stars. $^{16}O/^{17}O$ ratios of 425^{-100}_{+125} (in HD 178717), 500^{-100}_{+125} (in HD 121447), 100^{-50}_{+100} (in HD 101013), and 150 ± 50 (in HR 774) were found, together with $^{16}O/^{18}O$ ratios of 550^{-125}_{+225} (in HD 178717), 500^{-150}_{+250} (in HD 121447), and 60^{-30}_{+100} (in HD 101013). Lower limits were obtained for $^{16}O/^{17}O$ and $^{16}O/^{18}O$ in the mild barium stars *o* Vir and 16 Ser, and for $^{16}O/^{18}O$ in HR 774.

The $^{16}O/^{17}O$ ratios in HD 121447 and HD 178717 may be interpreted in terms of the dredge-up episodes occurring in intermediate-mass stars during the helium shell–flashing phase on the asymptotic giant branch, implying that the atmospheres of the barium stars have been contaminated by material from intermediate-mass companions which have completed their evolution. The $^{16}O/^{18}O$ ratio in HD 101013 is much lower than the ratios seen in stars in earlier evolutionary stages due to the helium burning of ^{14}N to ^{18}O in shell flashes; it may be used to constrain the peak temperatures encountered in the convective helium-burning shell during thermal pulses. The ^{18}O abundance in this and other barium stars implies that envelope burning (hot-bottom convection) has not occurred in these stars.

Subject headings: convection — stars: Ba II — stars: abundances — stars: interiors

I. INTRODUCTION

Observations of the $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios in several red giant stars have been reported by Harris and Lambert (1984*a*, *b*, hereafter HL1 and HL2). These results may be used as a basis for interpretation of the oxygen isotope ratios in stars which are believed to be further evolved, namely the barium, carbon, and S stars. In this paper results are presented for a group of classical and mild barium stars.

The Ba II stars do not fit into the current picture of the advanced stages of stellar evolution. They exhibit high abundances of barium and other *s*-process elements, which are thought to be synthesized in the double-shell source stage of stellar evolution on the asymptotic giant branch (AGB) and show somewhat enhanced carbon abundances which may be explained by helium burning during this evolutionary phase. Yet their luminosities are much lower than those expected for AGB stars. Their masses appear to be low ($\lesssim 2.5\ M_\odot$). The discovery that all Ba II stars are probably binaries (McClure, Fletcher, and Nemec 1980; McClure 1983) suggests the alternative possibility that the abundance features indicating advanced evolutionary state may be due to transfer of material from the companion star at the appropriate stage of its evolution.

Our abundance determinations were made by analysis of high-resolution 2.3 μm spectra. In this spectral region the first overtone vibration-rotation bands of the CO molecule's ground electronic state give rise to a large number of absorption lines, including lines due to the isotopically substituted species $^{13}C^{16}O$, $^{12}C^{17}O$, and $^{12}C^{18}O$. The stars examined were the Ba II stars HD 178717, HD 121447, HD 101013, and HR 774, and the mild barium stars *o* Vir and 16 Ser. Oxygen isotope ratios have not been hitherto published for any barium star.

II. OBSERVATIONS

High-resolution spectra of the six stars were taken at Kitt Peak National Observatory, using the Fourier transform spectrometer (Hall *et al.* 1978) at the coudé focus of the Mayall 4 m reflector. On the same nights, comparison spectra were taken of hot stars, except in the case of HR 774 (Table 1). Telluric lines in the barium star spectra were removed by ratioing that spectrum and the comparison spectrum using Beer's law, adjusting the air-mass ratio until the telluric lines were as far as possible eliminated. The cancellation of telluric lines was found to be best for weak lines, and therefore for spectra in which the telluric absorption was light (namely HD 178717, HD 121447, HD 101013, and *o* Vir). In HR 774 and 16 Ser, telluric absorption was heavy, and the cancellation of telluric lines was imperfect.

Several windows in the telluric absorption were identified between 4184 and 4294 cm^{-1}. In addition, the regions around the 2–0 band heads of $^{12}C^{18}O$ (4256.7 cm^{-1} at rest) and $^{13}C^{16}O$ (4264.7 cm^{-1} at rest) were examined, although their usefulness varied from star to star according to the extent of telluric absorption.

III. ANALYSIS AND RESULTS

Synthetic spectra were computed with the program MOOG (Sneden 1974) and compared with the observed spectra, the abundances of the species involved being varied feature by feature until the best fit was achieved to each feature. The abundances from the features were averaged to obtain the resulting abundances. All CO lines in the windows and regions of interest were included in the synthesis, employing the molecular constants of Dale *et al.* (1979) and the *gf* values of Chackerian and Tipping (1983). Atomic lines, with *gf* values from Kurucz and Peytremann (1975), were also included wherever they significantly affected the synthetic spectrum.

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TABLE 1

JOURNAL OF OBSERVATIONS

Object	Date	Spectral Region (cm^{-1})	Resolution (cm^{-1})	Integration Time (s)
HR 774	1980 Dec 28	3752.0–5315.7	0.076	13596
HD 121447	1981 Jun 18	3908.4–5211.1	0.064	15000
HD 178717	1981 Jun 18	3908.4–5211.1	0.064	10225
α Lyr	1981 Jun 18	3908.4–5211.1	0.064	2715
o Vir	1984 Mar 10	3908.4–5159.0	0.038	11281
α CMa	1984 Mar 10	3908.4–5159.0	0.038	3031
16 Ser	1984 Mar 11	3908.4–5159.0	0.038	12929
α Lyr	1984 Mar 11	3908.4–5159.0	0.038	4528
HD 101013	1984 Mar 12	3908.4–5159.0	0.038	13615
α CMa	1984 Mar 12	3908.4–5159.0	0.038	2060
HD 101013	1984 Mar 15	3908.4–5159.0	0.038	12970
α Lyr	1984 Mar 15	3908.4–5159.0	0.038	1712

The $\Delta v = 2$ sequence of the CN Red ($A\ ^2\Pi$–$X\ ^2\Sigma^+$) system is a prolific contributor of weak lines throughout the 2.3 μm region. All the detectable lines from the 0–2 through to the 4–6 bands of both $^{12}C^{14}N$ and $^{13}C^{14}N$ were included in the synthetic spectra. Both laboratory measurements and theoretical predictions were considered when assigning frequencies to these lines. Cerny *et al.* (1978) provide accurate measurements of $^{12}C^{14}N$ lines to a rotational quantum number $J'' \approx 60.5$ from the 0–2, 1–3, and 2–4 bands. Unpublished spectra of CN excited in an electrodeless discharge (Brault 1980) provided line frequencies for $^{12}C^{14}N$ and $^{13}C^{14}N$ lines to $J'' \approx 40.5$ in all bands considered here. A majority of the frequencies in our line list were derived from a set of predicted frequencies provided by a program written by Kotlar (1978) with molecular constants taken from Kotlar *et al.* (1979). Through a comparison of the predicted and measured frequencies, a set of corrections was obtained. For several bands examination of spectra of several cool carbon stars provided high J'' lines with which the corrections were extended to higher rotational quantum numbers. For some lines a considerable extrapolation of the corrections was involved; however, in all cases these lines are weak contributors to the stellar spectra.

The CN density in each stellar atmosphere was adjusted so that equivalent widths of CN lines near 4500 cm^{-1} were reproduced, as well as the few CN lines unblended with CO found in windows between 4275 and 4294 cm^{-1}. The 4500 cm^{-1} window was selected because the CN lines are of moderate intensity, CO lines are not present, and telluric lines are weak. Relative *gf*-values were computed from ab initio predictions of band oscillator strengths (Larsson, Siegbahn, and Ågren 1983). Thanks to our normalization procedures, the predicted CN line intensities are independent of the notoriously uncertain dissociation energy of CN. The primary (and small) uncertainty is probably the neglect of the vibration-rotation interaction; the CN lines among the CO lines come, on average, from higher rotational levels than the calibrating lines near 4500 cm^{-1}. However, our results from the unblended CN lines between 4275 and 4294 cm^{-1} agree well with our results from the lines near 4500 cm^{-1}, confirming that this effect is small.

Sample comparisons of synthetic and observed spectra are shown in Figs. 1, 2, and 4; observed spectra of two stars are shown in Figure 3. The model atmospheres used in the analysis were taken from Bell *et al.* (1976), interpolated to the values of $T_{\rm eff}$ and log g assigned to each star (Table 2). In all cases models computed with solar system abundances were used. Microturbulent velocities ξ were taken from Smith (1984) and Sneden, Lambert, and Pilachowski (1981); macroturbulent velocities Γ were adjusted to fit the profiles of the unblended lines observed in the region between 4269 and 4294 cm^{-1}; unblended lines are relatively common in this region, since it lies above the first-overtone band heads of most CO species.

In a few cases $^{12}C^{17}O$ and $^{12}C^{18}O$ lines are blended with $^{13}C^{16}O$ and $^{13}C^{14}N$ lines. We therefore measured $^{12}C/^{13}C$ ratios in these atmospheres. The $^{13}C^{16}O$ band head at 4264.7 cm^{-1} is formed by 2–0 band *R*-branch lines between *R*44 and *R*60. These lines, together with *R*35 and *R*38 in a window at lower wavenumber, were used to obtain $^{12}C/^{13}C$ ratios, the ^{12}C abundance being derived from strong low-excitation and weak high-excitation $^{12}C^{16}O$ lines in the region between 4269 and 4294 cm^{-1}. The results are presented in Table 3. An inability to cancel adequately the telluric led us to abandon an attempt to determine the $^{12}C/^{13}C$ ratio for HR 774; Smith's (1984) $^{12}C/^{13}C$ ratios were derived from the spectra listed in Table 1. The $^{12}C/^{13}C$ ratios found here are generally in good agreement with earlier results; the major exception is 16 Ser. This agreement suggests that the $^{16}O/^{17}O$ ratios derived by the same method are likely to be reliable. The above mentioned blending of $^{12}C^{17}O$ and $^{12}C^{18}O$ lines with lines of species containing ^{13}C has vary little effect on the determination of these ratios. Note in particular the good agreement between the $^{12}C/^{13}C$ ratios from CN and CO for HD 101013 and *o* Vir.

Several $^{12}C^{17}O$ lines of the *R* branch of the 2–0 band are visible in the windows in the telluric absorption between 4269 and 4294 cm^{-1}. In Table 4 these lines are listed and described for the case of HD 178717. Three of them (*R*21, *R*27, and *R*30) are virtually unblended, and abundances derived from these

TABLE 2

INPUT PARAMETERS FOR ABUNDANCE ANALYSIS

Object	$T_{\rm eff}$	Log g	Reference	ξ (km s^{-1})	Γ (km s^{-1})
HD 178717	4250	1.0	1	2.2	4.5
HD 121447	4250	1.0	2	2.2	4.5
HD 101013	4600	2.5	2	2.0	4.0
HR 774	4800	1.8	1	2.0	4.5
o Vir	4900	2.6	3	2.0	2.8
16 Ser	5000	3.0	3	2.3	3.0

REFERENCES.—(1) Smith 1984. (2) V. V. Smith 1984, private communication. (3) Sneden, Lambert, and Pilachowski 1981.

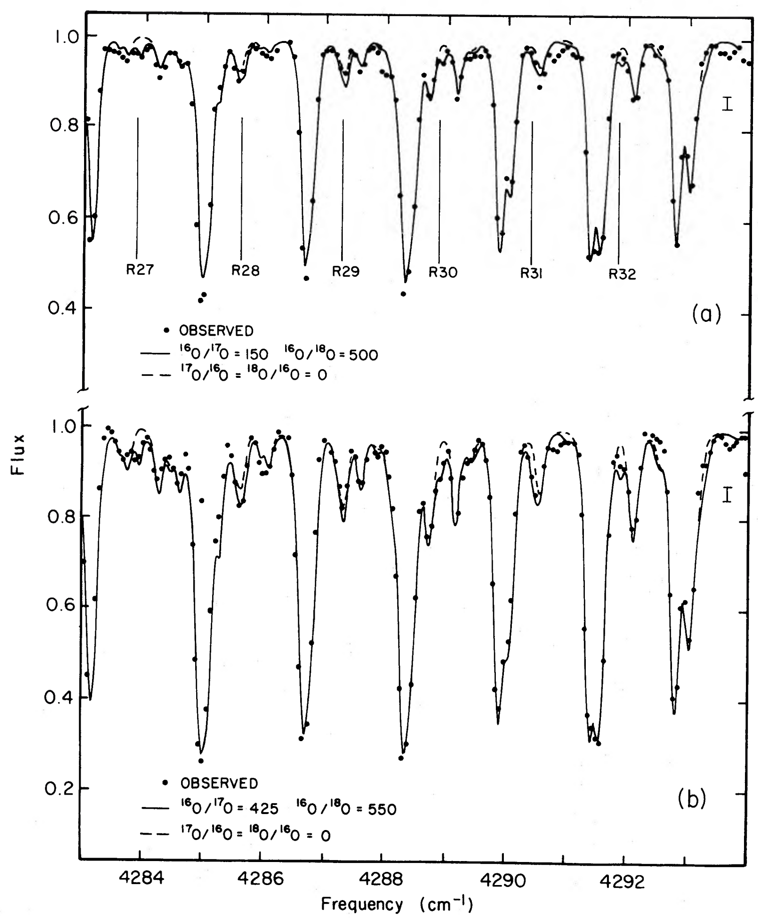

FIG. 1.—Comparison of selected observed and synthesized spectra for (*a*) HR 774 and (*b*) HD 178717. Positions of several 2–0 *R* band lines of $^{12}C^{17}O$ are indicated. The rms noise level is shown in the top right-hand corner.

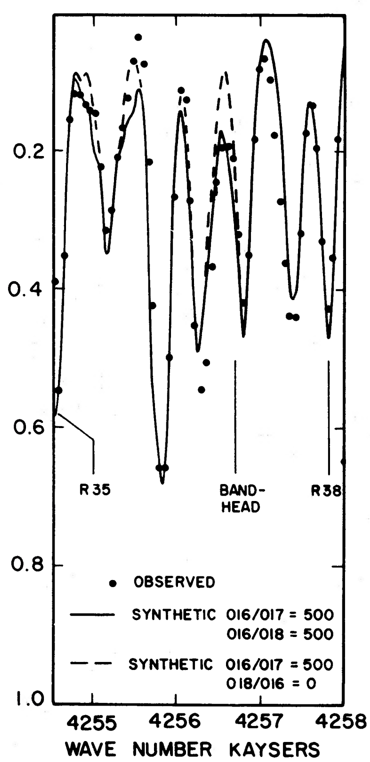

FIG. 2

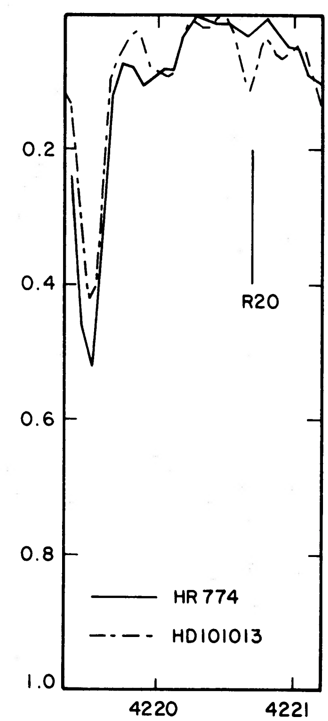

FIG. 3

FIG. 2.—Comparison of selected observed and synthesized spectra for HD 121447 around the region of the $^{12}C^{18}O$ 2–0 band head

FIG. 3.—Comparison of the observed spectra of HR 774 (*full line*) and HD 101013 (*dashed line*). The temperatures of the two stars are similar, and HD 101013, having a lower carbon abundance, should everywhere exhibit less intense lines. Note, however, the excess absorption in HD 101013 at 4220.69 cm^{-1}, corresponding to the position of 2–0 *R*20 line of $^{12}C^{18}O$.

lines were given double weight in the averaging. The agreement between the $^{16}O/^{17}O$ ratios deduced from different lines is generally good, with the exception of the abundance deduced from 2–0 *R*32, which is systematically higher than the ratios obtained from the other lines. It is believed that this is due to the blending of this line with two strong ^{12}CN lines and with a fairly strong ^{13}CN line, the positions of which are uncertain.

In the hotter stars in our sample the CO lines (particularly those due to the minor isotopes) are very weak due to the dissociation of CO molecules. In these stars the spectrum noise is a major cause of the line-to-line variation in the abundances deduced (see Fig. 1; the $^{12}C^{17}O$ features in HR 774 are about a factor of 2, and those in HD 178717 about a factor of 3, above the noise level). In the hottest stars (16 Ser and *o* Vir) only upper limits can be placed on the ^{17}O and ^{18}O abundances for this reason.

The determination of $^{16}O/^{18}O$ ratios from 2.3 μm spectra is much more difficult than the measurement of $^{16}O/^{17}O$, because $^{12}C^{18}O$ is a heavier molecule and all the lines are shifted deeper into the thicket of $^{12}C^{16}O$, $^{13}C^{16}O$, and $^{12}C^{17}O$ lines; and because the CN and telluric lines fall in unfavorable positions. Three lines of the 2–0 band of $^{12}C^{18}O$ (*R*7, *R*20, and *R*23) were found to lie generally outside the worst telluric absorption. All three are blended to a greater or lesser extent with CN lines, *R*20 at 4220.69 cm^{-1} being the least affected. The *R*29 line of the 1–3 band is heavily blended with CN and $^{12}C^{16}O$ lines but was visible in several stars. The lines between *R*44 and *R*59 around the 2–0 band head at 4256.7 cm^{-1} are blended to a lesser extent but are generally affected strongly by telluric absorption. In consequence the agreement between abundance determinations from different lines is poor, and the measured $^{16}O/^{18}O$ ratios are much less precise than the $^{16}O/^{17}O$ ratios (Table 3). Observations at 5 μm would provide confirmation of the $^{16}O/^{18}O$ ratios presented here; the 5 μm measurements of $^{16}O/^{17}O$ discussed by HL2 were in good agreement with 2.3 μm results.

A very high ^{18}O abundance was observed in HD 101013. Despite considerable line-to-line variations in the measured $^{16}O/^{18}O$ ratios, nearly all the lines mentioned above clearly show a ratio well below the value ~ 500 seen in ordinary red giants by HL2. Two spectra of this star were taken (Table 1),

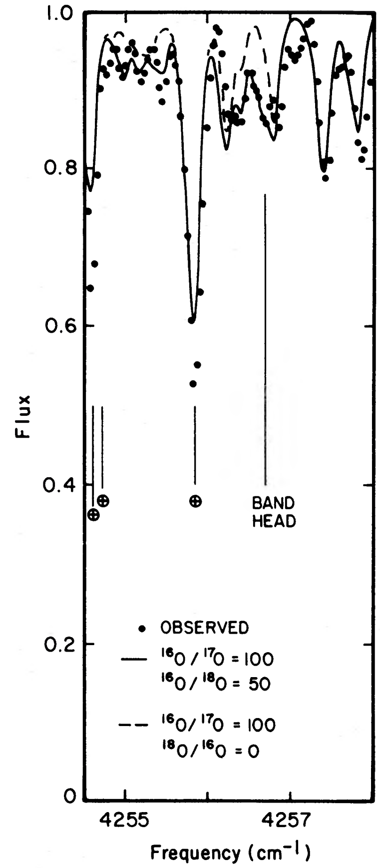

FIG. 4.—Comparison of selected observed and synthetic spectra for HD 101013 around the region of the $^{12}C^{18}O$ 2–0 band head. The positions of strong telluric lines are marked by $\oplus$.

and the $^{16}O/^{18}O$ ratios from both are in agreement within the uncertainty estimates. In Figure 4 a synthetic spectrum of the $^{12}C^{18}O$ band head region in HD 101013 is compared with the observed spectrum, showing that a ratio ~ 60 is required to explain the $^{12}C^{18}O$ features. There are expected to be a

TABLE 3

ABUNDANCES

Object	Log *N*(C)	Reference	$^{12}C/^{13}C$	Reference	$^{16}O/^{17}O$	$^{16}O/^{18}O$
HD 178717	8.7 ± 0.1	1	...	...	425^{-100}_{+125}	550^{-125}_{+225}
	8.6 ± 0.1	2	8	2		
HD 121447	8.8 ± 0.1	1	...	...	500^{-100}_{+125}	500^{-150}_{+250}
	8.7 ± 0.1	2	8	2		
HD 101013	8.4 ± 0.1	1	17^{-5}_{+8}	1	100^{-50}_{+100}	60^{-30}_{+100}
	...	...	13	3		
HR 774	8.7 ± 0.1	1	15	2	150 ± 50	$\gtrsim 500$
	8.7 ± 0.1	2	...	...		
	8.67	3	23	3		
o Vir	8.3 ± 0.1	1	15^{-4}_{+5}	1	$\gtrsim 170$	$\gtrsim 500$
	8.3	4	14	4		
	...	...	15	5		
16 Ser	8.3 ± 0.1	1	14^{-4}_{+6}	1	$\gtrsim 70$	$\gtrsim 70$
	8.47	4	25	4		
	...	...	33	5		

REFERENCES.—(1) This work. (2) Smith 1984. (3) Tomkin and Lambert 1979. (4) Sneden, Lambert, and Pilachowski 1981. (5) Tomkin, Luck, and Lambert 1976.

TABLE 4

^{17}O LINES DETECTED IN HD 178717

Line	Wavenumber[a] (cm^{-1})	Abundance[b]	Comment
2–0 *R*21	4271.941	340	
2–0 *R*22	4274.104	360	Slight blend with $^{12}C^{16}O$
2–0 *R*25	4280.170	370	Bad blend with HF
2–0 *R*27	4283.859	450	
2–0 *R*28	4285.597	430	Blend with ^{12}CN
2–0 *R*30	4288.858	400	Weak ⊕ absorption; blend with $^{12}C^{16}O$
2–0 *R*31	4290.381	600	Blend with ^{12}CN
2–0 *R*32	4291.833	1000	Blend with two ^{12}CN lines, a ^{13}CN line and $^{12}C^{16}O$

[a] Wavenumber at rest.

[b] ^{17}O abundance necessary to fit line expressed as $^{16}O/^{17}O$ ratio.

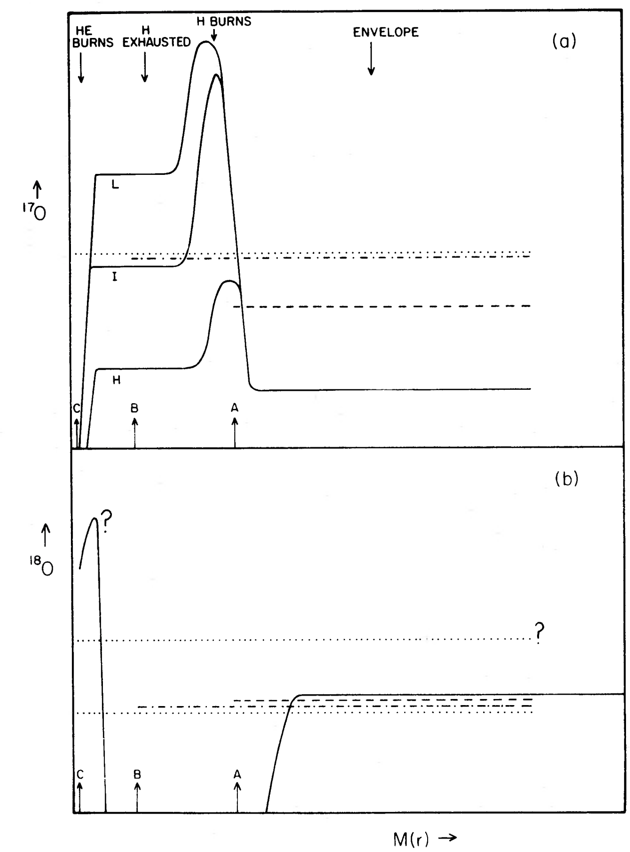

FIG. 5.—Schematic abundance profiles of (*a*) ^{17}O and (*b*) ^{18}O in evolved stars of $>1\ M_{\odot}$. Point A represents the lower limit reached by the first dredge-up; B, that reached by the second dredge-up; and C, that reached by the third dredge-up. The full lines represent the abundance profiles; in (*a*), the labels L, I, and H refer to abundances of ^{17}O estimated on the bases of the "low," "intermediate," and "high" values, respectively, of the $^{17}O(p, \alpha)^{14}N$ reaction rate from Fowler, Caughlan, and Zimmerman (1975). Dashed lines represent the envelope abundances after the first dredge-up; dot-dash lines, those after the second dredge-up; and dotted lines, those after several third dredge-up episodes (all envelope ^{17}O abundances estimated on the basis of the profile I). The profile marked "?" for ^{18}O does not arise in many stellar models; in those where it does, the post–third dredge-up ^{18}O abundance is represented by the dotted line marked "?."

number of unidentified lines due to heavy (*s*-process) elements present in this spectral region. However, it is highly unlikely that these are responsible for the strong absorption found in HD 101013 at the positions of the $^{12}C^{18}O$ lines, since they would also be expected in the spectra of the other stars. HR 774, in particular, has a similar temperature to HD 101013, and a similar (or higher) *s*-process enhancement, yet, as seen in Figure 3, the absorption in HD 101013 at the position of the 2–0 *R*20 line of $^{12}C^{18}O$ is much greater in HD 101013. However, bearing in mind the above remarks about uncertainties, confirmation of our result by observations at 5 μm is desirable. Observations of the fundamental vibration-rotation lines of the OH $^2\Pi$ ground state at 3–4 μm could also yield a $^{16}O/^{18}O$ ratio for this star if the ^{18}O abundance is as large as we have found.

The major source of uncertainty in our measurements is the effect of blending due to CN lines. This introduces both a random error (due to insufficient knowledge of the CN molecular constants and *gf* values) and a systematic uncertainty due to the error in the CN abundance determination. The error estimates in Table 3 include estimates of the uncertainty due to these factors. Errors due to uncertainties in the model atmosphere parameters were found to be small (<5%). In the case of HR 774 the poor resolution (Table 1) introduces an extra uncertainty into the error estimates.

IV. DISCUSSION

a) Evolution of Oxygen Isotopes through the Third Dredge-up

In stars which are sufficiently massive to undergo CNO-cycle hydrogen burning, the behavior of the oxygen isotopes may be presented schematically as in Figure 5. The low initial ^{17}O abundance ($^{16}O/^{17}O = 2660$, the solar system abundance ratio) is enhanced at sufficiently high temperatures by proton captures on the abundant ^{16}O nucleus, followed by β-decay, i.e., $^{16}O(p, \gamma)^{17}F(e^+\nu)^{17}O$. At still higher temperatures the CNO cycles come into equilibrium, with the reaction $^{17}O(p, \alpha)^{14}N$ destroying ^{17}O, forming an equilibrium $^{16}O/^{17}O$ ratio whose value is uncertain due to uncertainties in the $^{17}O(p, \alpha)$ reaction rate, but which is certainly well below the initial ratio. The ^{17}O abundance profile within the star thus goes through a peak at approximately the position of maximum hydrogen burning; this peak, of course, gradually moves outward in mass from the center of the star as hydrogen shell burning begins and proceeds. When helium burning begins inside the hydrogen-burning shell, the ^{17}O is expected to be completely destroyed in that region by the reaction $^{17}O(\alpha, n)^{20}Ne$.

The isotope ^{18}O, on the other hand, is expected to be destroyed during hydrogen burning by the reaction $^{18}O(p, \alpha)^{15}N$, so that it virtually disappears from the hydrogen-burning region and from the hydrogen-exhausted CNO equilibrium region within it. When helium burning starts, the ^{14}N which is the major residue of CNO cycling of the initial C, N, and O isotopes undergoes the reactions $^{14}N(\alpha, \gamma)^{18}F(e^+\nu)^{18}O$ followed by $^{18}O(\alpha, \gamma)^{22}Ne$. The ^{18}O abundance profile in the helium-burning region therefore goes through a peak whose amplitude depends on the relative rates of the reactions $^{14}N(\alpha, \gamma)$ and $^{18}O(\alpha, \gamma)$, and, thus, on the helium-burning temperature; current stellar models predict that helium shell burning is unstable against shell flashes in which high temperatures ($> 2 \times 10^8$ K) are attained, so that $^{18}O(\alpha, \gamma)$ rapidly destroys ^{18}O, and the abundance peak is negligible.

A succession of convective mixings of the outer layers of the star brings to the surface matter affected by these nuclear transformations. The first such dredge-up occurs in all stars when they become red giants at the onset of shell hydrogen burning. At this time in stars of $\gtrsim 1\ M_\odot$ the base of the convective envelope reaches a point such as A (Fig. 5), so that a portion of the ^{17}O abundance peaks is mixed into the envelope. The $^{16}O/^{17}O$ ratio at the surface is reduced from its assumed original value 2660 to a value not less than ~ 440 depending on the star's mass (Dearborn and Gough 1984). Six of the nine stars studied by HL1 and HL2 show broad agreement with the expected trend of $^{16}O/^{17}O$ with mass (a seventh has a value within the expected range, but its mass is so uncertain that a meaningful comparison cannot be made). Mixing down to point A also implies the inclusion in the envelope of matter depleted in ^{18}O (Fig. 5*b*), causing a small increase in the surface $^{16}O/^{18}O$ ratio (the observations by HL1 and HL2 are compatible with this). The envelope abundances subsequent to this first dredge-up are represented schematically by dashed lines in Figure 5.

The next dredge-up occurs at the end of core helium burning for stars of $\gtrsim 4.5\ M_\odot$ only (Kippenhahn, Thomas, and Weigert 1965; Iben and Renzini 1983). The convective envelope extends down to a point such as B (Fig. 5), bringing up the entire ^{17}O abundance peak and a portion of the hydrogen-exhausted zone which is also (relative to the envelope) enriched in ^{17}O. The $^{16}O/^{17}O$ ratios expected after this second dredge-up cannot be specified exactly due to the uncertainty in the $^{17}O(p, \alpha)$ reaction rate (see the three curves in Fig. 5*a*), and predictions of these ratios have not hitherto been published (Iben and Truran 1978, and Iben and Renzini 1983 present approximations for the effect of the second dredge-up on surface abundances, but these are not applicable to ^{17}O). We have made approximate calculations of the expected $^{16}O/^{17}O$ ratios based on Hofmeister, Kippenhahn, and Weigert's (1964) model of a 7 $M_\odot$ star at the end of core helium burning, and on Iben and Renzini's (1983) specification of the second dredge-up. Prior to the second dredge-up, envelope abundances were assumed to be those left by the first dredge-up, with $^{16}O/^{17}O \approx 600$ (appropriate for a 7 $M_\odot$ star according to Dearborn and Gough 1984). We find that $^{16}O/^{17}O \approx 500$ if the maximum possible value of the $^{17}O(p, \alpha)$ reaction rate is used, $^{16}O/^{17}O \approx 140$ if the minimum possible value is used, and $^{16}O/^{17}O \approx 300$ if the recommended ("intermediate") value from Fowler, Caughlan, and Zimmerman (1975) is used. Two of the stars analyzed by HL2 were found to have $^{16}O/^{17}O \approx 200$, markedly lower than the ratios in the other stars. These ratios may plausibly arise from the second dredge-up; whether or not this is the case, since the ^{17}O must have come from the same abundance peak, they suggest that the $^{17}O(p, \alpha)$ reaction must have a rate near the low end of the allowed range. As with the first dredge-up, the second dredge-up will in general cause a small increase in the surface $^{16}O/^{18}O$ ratio due to the admixture of matter depleted in ^{18}O (see below). The envelope abundances after the second dredge-up, in those stars which experience it, are represented schematically by dot-dashed lines in Figure 5.

The third dredge-up occurs in the subsequent helium shell–burning phase of evolution in stars of $\gtrsim 2\ M_\odot$ (Iben and Renzini 1983), in the intervals between shell flashes. Each dredge-up reaches down to a point such as C (Fig. 5), bringing up a small amount of helium-burned material enriched in ^{12}C and probably also *s*-process elements. For our purposes the important fact to note is that *the third dredge-up must mix the entire* ^{17}O *abundance peak into the envelope* (even if the second dredge-up has not already done so). Stars which have started to undergo shell flashing and the third dredge-up process therefore *must* have $^{16}O/^{17}O$ ratios $\lesssim 200$, since we concluded above that the $^{17}O(p, \alpha)$ reaction rate cannot be far from the minimum experimentally allowed value.

Even lower $^{16}O/^{17}O$ ratios are expected in those stars in which hot-bottom convection (envelope burning) occurs. In such stars the temperatures in the lower levels of the envelope are so high that CNO–cycle reactions occur; the convection ensures that most or all of the envelope undergoes this CNO–cycling. The $^{16}O/^{17}O$ ratio at the surface will then approach CNO equilibrium values (on the order 20–50). This is expected to occur for stars of above 3–4 $M_\odot$ (Renzini and Voli 1981; Renzini 1984).

The effect of the third dredge-up on the $^{16}O/^{18}O$ ratio will depend on whether or not ^{18}O abundance peak exists (Fig. 5*b*) and whether or not hot-bottom convection occurs and will be discussed in a separate section.

b) The $^{16}O/^{17}O$ *Ratio in Barium Stars*

The atmospheres of the barium stars show definite signs of contamination by material which has experienced the third dredge-up process outlined above. They are carbon rich relative to red giants in earlier stages of evolution (Tomkin and Lambert 1979; Sneden, Lambert, and Pilachowski 1981; Kovács 1983; Smith 1984). This admixture of ^{12}C was surely produced by the triple-alpha reaction in helium burning. They also show large enhancements of the *s*-process elements, for which the proposed neutron sources require helium burning (see below). The fact that the masses, luminosities, and temperatures of the Ba II stars do not agree with third dredge-up models, together with the fact that they all appear to be binaries, has led to the suggestion that these third dredge-up abundance peculiarities arose in the envelope of a more massive companion star, and are now seen in the barium star as a consequence of mass transfer from the companion (which has since evolved to a faint, compact object). It would be reasonable to expect that, whichever star experienced the third dredge-up, the oxygen isotopes should reflect its occurrence.

In general the $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios found here are similar to those found by HL1 and HL2 in ordinary (i.e., pre–third dredge-up) red giants, the exception being the $^{16}O/^{18}O$ ratio in HD 101013, which can probably be explained by the same helium burning that produced the ^{12}C and *s*-process enhancements (see below). At least two of the stars, HD 121447 and HD 178717, have $^{16}O/^{17}O$ ratios which are incompatible with the ratios <200 which are expected from the third dredge-up. It follows that these stars cannot themselves have undergone the third dredge-up, nor any kind of mixing (e.g., that due to the helium core flash, as suggested by Sneden, Lambert, and Pilachowski 1981) which would bring up material from below the ^{17}O abundance peak, since it is difficult to imagine any process which could bring helium-burned material to the surface without disturbing the ^{17}O-rich layer in between. (Plume mixing [Ulrich 1973; Scalo and Ulrich 1973] might be such a process, although the effect of "entrainment" as described by Scalo and Ulrich would be to mix a great deal of ^{17}O-rich material into the plumes.) We conclude that, at least in these two stars, the carbon and *s*-process enhancements probably cannot be due to nucleosynthesis in the stars' own interiors but must reflect the presence of material transferred from above onto the stars' surfaces.

The fact that transferred material from a post–third dredge-up envelope must have had a $^{16}O/^{17}O$ ratio $\lesssim 200$ implies that, in the stars with $^{16}O/^{17}O \approx 500$, it must have been rather heavily diluted by material from the stars' own envelopes with much higher $^{16}O/^{17}O$ ratios; alternatively, if these stars were then on the main sequence, their subsequent first dredge-up must have brought up very little ^{17}O. Either way this implies that their masses are rather low (close to 1 $M_\odot$, below which ^{17}O is not enhanced by the first dredge-up). Some support is lent to this hypothesis by Smith's (1984) measurements of the *s*-process enhancements in HR 774, HD 121447 and HD 178717; HR 774, in which on this hypothesis the transferred material was less diluted by the star's own envelope, since its $^{16}O/^{17}O$ ratio is closer to what would be expected from the third dredge-up, shows higher *s*-process and carbon enhancements than the other two stars.

An alternative possibility is that, as suggested by Pinsonneault, Sneden, and Smith (1984), only a small amount of nearly pure helium-burned material rich in ^{12}C and *s*-process elements was transferred. This implies that mass transfer onto the barium star did not take place until the evolved star had lost the whole of its enveloped and was ejecting material from its helium-burned zone at its surface. This ^{17}O-depleted material rich in ^{12}C and *s*-process elements (and ^{18}O, in the case of HD 101013) would be so small in quantity that the $^{16}O/^{17}O$ ratio in the barium star envelope would be virtually unaffected by its incorporation and would evolve in the normal fashion as described above.

c) Helium Shell Flashes and the $^{16}O/^{18}O$ *Ratio in HD 101013*

Becker and Iben (1979) present stellar models in which the second dredge-up penetrates into the helium-rich core as far as layers in which the ^{14}N left by the CNO cycle has undergone the reactions $^{14}N(\alpha, \gamma)^{18}F(e^+\nu)^{18}O$ (i.e., the point B in Fig. 5*b* overlaps with the ^{18}O abundance peak), so that the surface layers are enriched in ^{18}O. However, it appears that reduction of the $^{16}O/^{18}O$ ratio to values as low as ~ 100 only occurs in stars of very low metallicity. The second dredge-up is therefore unlikely to be the cause of the low $^{16}O/^{18}O$ ratio observed in HD 101013.

A more probable cause is the same reaction sequence occurring in the convective shell which arises in the helium-rich zone during shell flashes (thermal pulses) in the subsequent AGB phase. This convective shell is thought to be the most likely site of neutron production, by which the *s*-process overabundances in barium and carbon stars may be explained (Iben 1975). It is also obvious that helium burning in this shell can produce the ^{12}C seen in C and Ba II stars. The $^{16}O/^{18}O$ ratios expected, after diluting with envelope material the ^{18}O from $^{14}N(\alpha, \gamma)$ to the same extent as the observed dilution of ^{12}C and the *s*-process elements, would be ~ 100 as observed in HD 101013.

Iben (1982, 1983) and Iben and Renzini (1982) have suggested that in low-mass thermally pulsing AGB stars, hydrogen may be transported downward from the envelope into the helium-rich zone, either by diffusion or by semiconvective mixing, during the intervals between shell flashes. During the next shell flash the ^{12}C produced in helium burning reacts with these protons and with the remaining helium in the sequence $^{12}C(p, \gamma)^{13}N(e^+\nu)^{13}C(\alpha, n)^{16}O$, the neutrons released in the last step being necessary for the *s*-process. At the same time $^{14}N(\alpha, \gamma)$ would produce ^{18}O in the usual manner. However, since ^{18}O is rapidly destroyed by $^{18}O(p, \alpha)$ in the presence of protons [whose rate at helium-burning temperatures is up to 10^4 times that of $^{12}C(p, \gamma)$], this neutron source cannot have operated during the shell flashes in which ^{18}O was produced in the HD 101013 primary (though it may have occurred during subsequent flashes, after the ^{18}O had been mixed into the envelope).

Current models of the behavior of the convective shell in more massive ($\gtrsim 2\ M_\odot$) AGB stars predict that once the ^{14}N has been burned to ^{18}O it should undergo further α-captures in the sequence $^{18}O(\alpha, \gamma)^{22}Ne(\alpha, n)^{25}Mg$, the last step being a neutron source for the *s*-process (and the most important neutron source in intermediate mass stars). In terms of Figure 5*b*, the ^{18}O peak in the helium-burning zone does not occur. Mixing of small quantities of shell material into the stellar envelope in the interpulse phase would then enhance the ^{12}C and *s*-process abundances with very little effect on the $^{16}O/^{18}O$ ratio. This is consistent with the $^{16}O/^{18}O$ ratios in HD 178717, HD 121447, and probably HR 774 and *o* Vir, since these $^{16}O/^{18}O$ ratios are similar to those seen in less-evolved red giants (HL1, HL2). However, the high ^{18}O abundance in HD 101013 shows that in at least some shell flashes in at least some stars, the above reaction sequence does not proceed beyond ^{18}O.

In the least massive AGB stars to undergo this type of third dredge-up ($\sim 2\ M_\odot$) the theoretical temperature at the base of the convective shell is $\sim 2.0 \times 10^8$ K in the earliest shell flashes, the duration of the pulse being $\sim 10^9$ s (Iben and Truran 1978); the rate of destruction of ^{18}O also depends on the $^{18}O(\alpha, \gamma)$ reaction rate and on the product of the density ρ and the ^4He abundance X_4 in the shell, which according to Iben (1977) is generally $\rho X_4 \approx 2.2 \times 10^3$ g cm^{-3}. The temperature increases with successive shell flashes and with increasing stellar mass. For temperatures above 2×10^8 K, ^{18}O would be rapidly burned to ^{22}Ne, as is theoretically expected. The pulse duration and ρX_4 are unlikely to be greatly in error, and the $^{18}O(\alpha, \gamma)$ reaction rate at these temperatures is well determined (Harris *et al.* 1983); therefore, for ^{18}O to survive in the convective shell the maximum temperature must have been rather lower than the theoretical value in at least some of the HD 101013 companion star's shell flashes. (Since the temperature increases with successive flashes, these must have been the earliest flashes.) On the basis of the above figures, the maximum convective shell temperature cannot have been higher than 1.9×10^8 K. Perhaps the star did not experience the later, hotter shell flashes because it then filled its Roche lobe.

It is possible that, in shell flashes subsequent to those in which ^{18}O was synthesized, the reaction sequence from ^{14}N through ^{25}Mg proceeded further than ^{18}O, with the $^{22}Ne(\alpha, n)$ neutron source giving rise to the observed *s*-process elements. However, the conclusion of Tomkin and Lambert (1979) that in HR 774 the $^{22}Ne(\alpha, n)^{25}Mg$ reaction has not contributed to that star's Mg isotopes implies that this did not occur, and that the neutron source was probably the $^{13}C(\alpha, n)$ reaction as described above. (It also implies that the maximum temperature in the convective shell during a shell flash was never higher than $\sim 2.5 \times 10^8$ in *any* of this star's flashes.)

The observed ^{18}O abundance in three stars (HD 178717, HD 121447, and HD 101013) also enables a limit to be put on the extent to which hot-bottom convection occurred in their companions, since ^{18}O will be destroyed if hot-bottom convection occurs to any appreciable extent. In order for ^{18}O to survive in hot-bottom envelopes, the base temperature must be $< 4 \times 10^7$ K (Renzini and Voli 1981), whereas current stellar models predict higher temperatures than this in stars with masses $\gtrsim 3\ M_\odot$ or less. Combining this with the argument above from the observed ^{18}O abundance in HD 101013, it can be deduced that the Ba II star primaries probably had masses in the range ~ 1–$3\ M_\odot$. If the HR 774 primary (in which, as argued above, the $^{22}Ne(\alpha, n)$ reaction did not occur) is a typical case, then this range can be further restricted, since the other plausible neutron source, $^{13}C(\alpha, n)$, has only been encountered theoretically in stars of mass $\lesssim 1\ M_\odot$.

V. CONCLUDING REMARKS

We may draw three main conclusions from the results reported here. First, in at least two stars (HD 121447 and HD 178717) the $^{16}O/^{17}O$ ratios imply the addition of material enriched in *s*-process elements from the envelope of a companion star, confirming the barium star formation mechanism proposed by McClure, Fletcher, and Nemec (1980) and McClure (1983). Second, in at least one star (HD 101013 or, more probably, its now evolved companion) the shell helium-burning temperature was lower than theoretically expected, being low enough for ^{14}N to be burned to ^{18}O but not further. Low helium-burning temperatures favor the reaction $^{13}C(\alpha, n)^{16}O$ rather than $^{22}Ne(\alpha, n)^{25}Mg$ as the source of neutrons for the *s*-process. In at least one other star (HR 774 according to Tomkin and Lambert 1979) the neutron source for the *s*-process cannot have been $^{22}Ne(\alpha, n)$ and was therefore probably $^{13}C(\alpha, n)$. Third, none of the barium stars shows evidence of having undergone hot-bottom convection (envelope burning), and three of them (HD 121447, HD 178717, and HD 101013, or rather their hypothetical evolved companions) certainly did not experience hot-bottom convection. Further measurements using 5 μm CO spectra are desirable in order to confirm the $^{16}O/^{18}O$ ratios measured here (see § III for a discussion of the uncertainty in these ratios). If the ^{18}O abundance in HD 101013 is as high as we have found, measurements of $^{16}O/^{18}O$ using 3–4 μm OH spectra might also be feasible.

We would like to thank Dr. J. Brault for providing an unpublished laboratory spectrum of CN, Dr. K. H. Hinkle for assistance at the telescope, and Dr. J. F. Dominy for providing a set of predicted CN line frequencies. We are indebted to Professor H. J. Smith for support and encouragement. This work was supported in part by the National Science Foundation (grant AST 83-16635) and the Robert A. Welch Foundation of Houston, Texas.

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