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OXYGEN ISOTOPIC ABUNDANCES IN EVOLVED STARS. IV. FIVE K GIANTS

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ABSTRACT

Oxygen isotopic ratios have been measured in the atmospheres of α UMa, β Gem, β UMi, α Ari, and α Ser. The ratios are found to lie within the ranges $240 \leq {}^{16}O/{}^{17}O \leq 520$ and $400 \leq {}^{16}O/{}^{18}O \leq 600$. It is shown that some of the stars in this and previous samples have probably experienced the helium core flash, and that the $^{16}O/^{17}O$ ratios tend to confirm that "extramixing" of CNO-cycled material into the stars' envelopes has occurred as a result of the flash.

The oxygen isotopic ratios are much smaller than the anomalously high ratios seen in stars in the later thermal-pulsing stage of evolution. Hence, the anomalous ratios cannot be explained by the helium core flash. It is proposed that they are due to the addition by the third dredge-up mechanism of helium-burned material which is devoid of both ^{17}O and ^{18}O and therefore dilutes the ^{17}O and ^{18}O abundances acquired during earlier evolutionary stages. This process may also explain the oxygen isotope ratios seen in barium stars, if these are formed by mass transfer from a thermally pulsing binary companion.

Subject headings: nucleosynthesis — stars: abundances — stars: interiors — stars: late-type

I. INTRODUCTION

Measurements of the oxygen isotopic abundance ratios $^{16}O/^{17}O$ and $^{16}O/^{18}O$ in normal (i.e., solar-metallicity) late-K and M type giants (Harris and Lambert 1984*a*, *b*, hereafter HL1, HL2) are in broad agreement with theoretical predictions of the results of the first dredge-up, which occurs in stars on their first ascent of the giant branch. The same is true of the abundances of the other CNO elements and isotopes (with small modifications to explain the $^{12}C/^{13}C$ ratios: Lambert 1981; Lambert and Ries 1981; HL1; HL2).

Measured oxygen isotopic ratios in stars of more advanced evolutionary phase—the MS and S stars (Harris, Lambert, and Smith 1985*b*, hereafter HLS) and N-type carbon stars (Harris *et al.* 1987) believed to lie on the asymptotic giant (AGB)—are in conflict with theoretical expectations, whereas the other CNO abundances can be explained by the shell flash and third dredge-up mechanism reviewed by Iben and Renzini (1983). The oxygen isotopic ratios in the AGB stars are much larger than expected, and have proved extremely difficult to explain. One of the hypotheses advanced for them by HLS traces them to destruction of ^{17}O and ^{18}O during the helium core flash in low-mass stars. The purpose of this paper is to seek evidence for this hypothesis.

The normal red giants referred to above are believed to be in the shell hydrogen-burning stage of evolution, while the AGB stars are in the double-shell burning stage. The helium core flash terminates shell hydrogen burning in low-mass stars, and inaugurates the phase immediately prior to the AGB, i.e., core helium burning. If anomalously large oxygen isotope ratios were found in low-mass core helium-burning stars, the core-flash hypothesis would be substantiated.

Core helium-burning stars of low mass ($\lesssim 3\ M_\odot$) and near-solar metallicity are expected to lie in the "clump" region of the H-R diagram. We have therefore measured oxygen isotope ratios in the atmospheres of five K giants whose temperatures and luminosities suggest that they either occupy or are near this position in the H-R diagram. We made use of lines of the fundamental vibration-rotation bands of the CO molecule near 5 μm in the same manner as HL1 and HL2. A high density of CO lines in this region, though it leads to considerable blending among them, ensures that many $^{12,13}C^{17}O$ and $^{12,13}C^{18}O$ lines are identifiable and measurable.

II. OBSERVATIONS, ANALYSIS, AND RESULTS

Spectra of the stars listed in Table 1 were acquired at 5 μm using the Fourier transform spectrometer (FTS; Hall *et al.* 1978) at the coudé focus of the Kitt Peak National Observatory's 4 m reflector. The observing run spanned the period 1986 January 26–28. A lunar spectrum was obtained on January 26; this spectrum is the thermal emission spectrum of the lunar surface and not that of reflected sunlight. After apodization to a resolution of 0.0089 cm^{-1} (equivalent to about 1.3 km s^{-1}), each stellar spectrum was divided by the lunar spectrum according to Beer's law in order to remove telluric absorption lines as far as possible. The signal-to-noise ratios range from 90 (β Gem) to 31 (α Ser). Windows between strong telluric lines were identified by HL1 and HL2.

Our analysis closely followed that used by HL1 and HL2. Synthetic spectra calculated with the program MOOG (Sneden 1974) were compared with the observed spectra. All CO lines of all isotopic species were included in the synthesis. The model atmospheres used in the syntheses were taken from the Bell *et al.* (1976) series, interpolated where necessary to the chosen values of effective temperature $T_{\rm eff}$ and surface gravity log *g* of the program stars (see Table 2). The model atmospheres all had solar system abundances. Microturbulent and macroturbulent velocities (ξ and Γ, respectively) were introduced in order to fit the depths and profiles of unblended CO lines. It was also necessary to treat the ^{12}C abundance and $^{12}C/^{13}C$ ratio as input parameters for the purpose of locating

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TABLE 1

INPUT PARAMETERS FOR ABUNDANCE ANALYSIS

Object	T_{eff} (*K*)	log *g* (cm s^{-2})	log ε(C)[a]	$^{12}C/^{13}C$[b]	ξ (km s^{-1})	Γ (km s^{-1})
β Gem	5000	3.00	8.50	18 (16)	1.5	3.3
α UMa	4750	2.25	8.55	19 (22)	1.0	4.5
α Ari	4700	2.51	8.60	22 (19)	1.5	2.4
α Ser	4420	2.50	8.40	16 (14)	1.8	1.8
β UMi	4340	1.86	8.55	12 (11)	2.0	3.0

[a] Logarithm of carbon abundance relative to log ε(H) = 12.0.

[b] The final estimate is followed (in parentheses) by the ratio derived from CN red and near-infrared lines, as compiled by Lambert and Ries 1981.

TABLE 2

OXYGEN ISOTOPIC ABUNDANCES

	NUMBER OF FEATURES				
STAR	^{17}O	^{18}O	$^{17}O+^{18}O$	$^{16}O/^{17}O$	$^{16}O/^{18}O$
β Gem	19	8	1	240^{-50}_{+60}	510^{-90}_{+110}
α UMa	16	7	3	330^{-50}_{+70}	600^{-125}_{+150}
α Ari	19	10	2	520^{-100}_{+120}	450^{-90}_{+110}
α Ser	15	5	1	300 ± 150	400 ± 200
β UMi	14	12	1	510^{-70}_{+90}	440^{-70}_{+90}

the continuum in this heavily blended region, as described by HL1 and HL2 (this continuum problem is less severe for the relatively hot stars considered here, since the blending CO lines are relatively weaker than in the stars considered by HL1 and HL2). First estimates of all these input parameters were obtained from the literature (Tomkin and Lambert 1974; Tomkin, Lambert, and Luck 1975; Tomkin, Luck, and Lambert 1976; Lambert and Ries 1977, 1981; Kjaergaard *et al.* 1982; Gratton 1985) and were adjusted slightly to give the best fits in our spectra. The complete set of input parameters is shown in Table 1. The adjusted $^{12}C/^{13}C$ ratios are in good agreement with the CN-based values listed by Lambert and Ries (1981).

Our results for the oxygen isotopic ratios (the means of the values found for each isotopic feature in the spectrum) are presented in Table 2. As HL1 and HL2 found, the most significant source of error is, in general, the uncertainty in the $^{12}C^{16}O$ and $^{13}C^{16}O$ abundances assumed. Errors due to the internal scatter of the measurements of the ^{17}O and ^{18}O features are in general much smaller than HL1 and HL2 found, since their spectra were contaminated by an intensity modulation of instrumental origin, which has since been eliminated from the FTS. Uncertainties in the other model atmosphere parameters produce rather small errors in our measured isotope ratios (HL1 and HL2), since our basic procedure of comparing $^{12,13}C^{17,18}O$ lines with relatively weak $^{12,13}C^{16}O$ lines tends to make them cancel out. In particular, the fact that the adopted effective temperatures are, in general, systematically too high (see below) should not introduce a significant error in the final isotopic ratios (see HL1).

Observed and synthetic spectra for two of our stars are compared in Figures 1 and 2. With the final adjustments of the ^{17}O

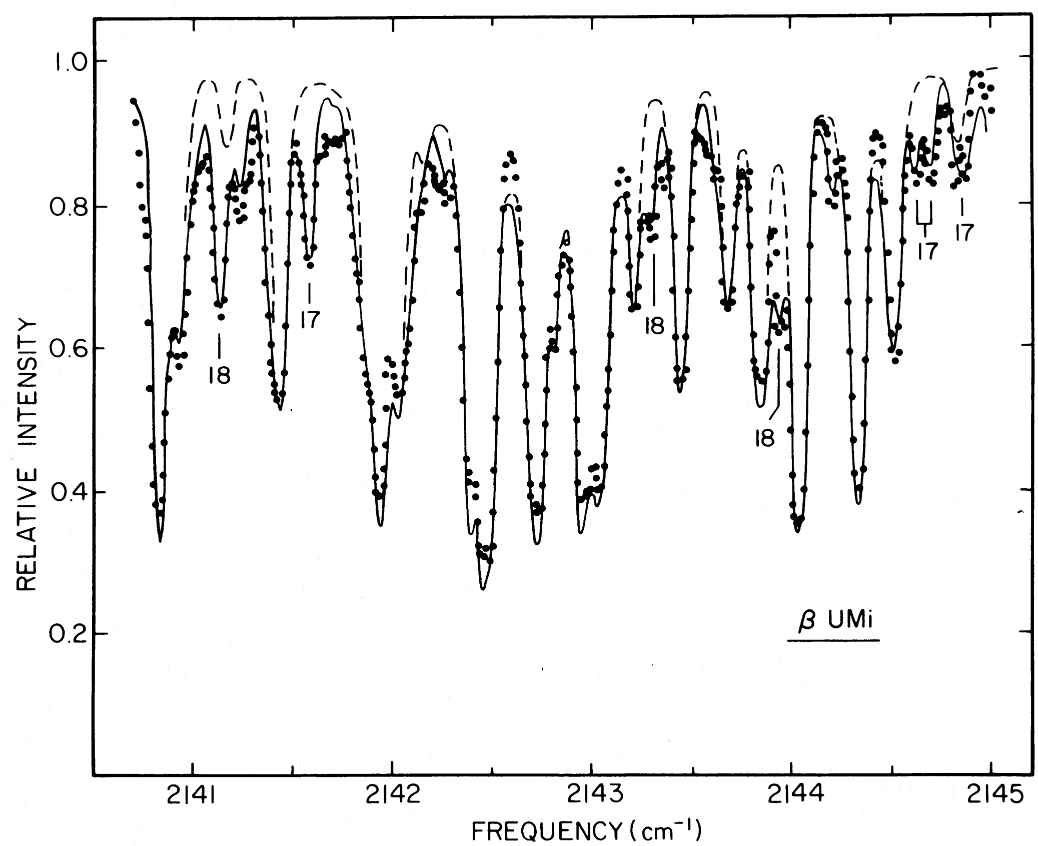

FIG. 1.—Comparison of observed and synthesized spectra of β UMi. Synthetic spectra are shown for $^{16}O/^{17}O = {}^{16}O/^{18}O = 0$ (*dashed line*) and $^{16}O/^{17}O = 510$ and $^{16}O/^{18}O = 440$ (*solid line*). Principal contributors to some of the weaker lines are identified: $17 \equiv {}^{12}C^{17}O$ and $18 \equiv {}^{12}C^{18}O$.

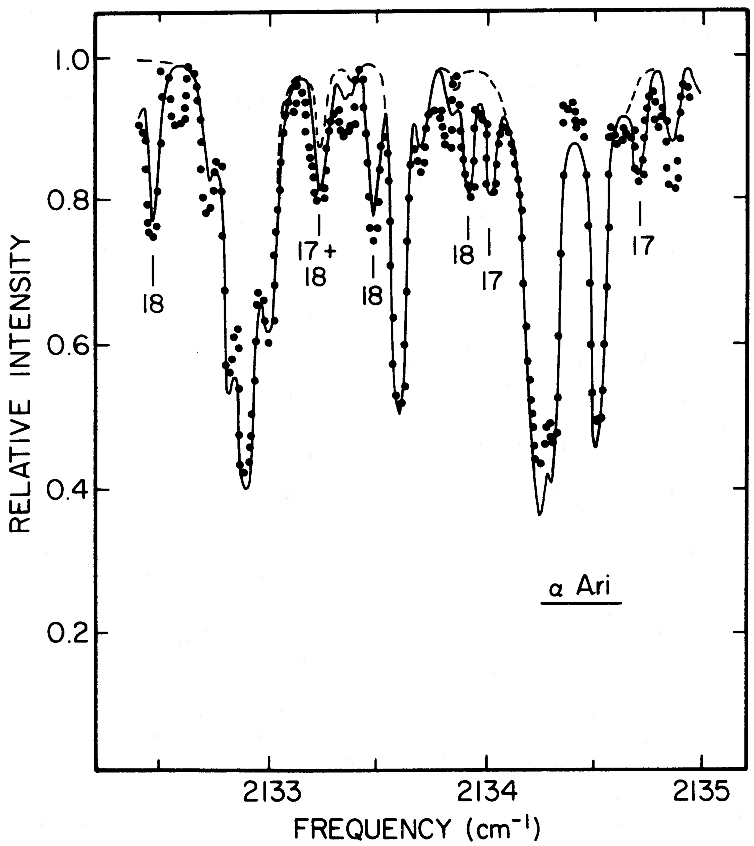

FIG. 2.—Comparison of observed and synthesized spectra of α Ari. Synthetic spectra are shown for $^{16}O/^{17}O = {}^{16}O/^{18}O = 0$ (*dashed line*) and $^{16}O/^{17}O = 520$ and $^{16}O/^{18}O = 450$ (*solid line*). Principal contributors to some of the weaker lines are identified: $17 \equiv {}^{12}C^{17}O$ and $18 \equiv {}^{12}C^{18}O$.

and ^{18}O abundances, the synthetic spectrum is a reasonably good simulation of the observed spectrum. A few weak unidentified lines are present; no attempt was made to provide a complete list of atomic and molecular (other than CO) lines. The cores of the very strong CO lines are formed in the extremely high layers of the atmosphere and are sensitive to the conditions found there (Heasley *et al.* 1978). The depths of these lines in a synthetic spectrum can be controlled by where one chooses to truncate the highest layer in a model atmosphere. While such strong lines could shed new light on the upper atmospheric levels and possible chromospheres, the weaker lines on which our isotopic ratios are based are formed in the photosphere, and are insensitive to the upper atmosphere or chromospheric structure. In this study of isotopic ratios, we ignore the information in the strongest lines, and, for cosmetic reasons, retain only those upper layers of the model atmosphere which provide a good fit to the strong lines. Typically, these line cores form at continuum optical depths of 10^{-4} to 10^{-5}.

One star, α Ser, was found to show a doubling of many of its CO lines, the origin of which is uncertain. No such doubling has been reported for α Ser before, and no clear evidence of it can be seen in a 1.6 μm spectrum of the second-overtone CO bands taken in 1982 February. Since it is seen in two spectra of α Ser taken on the same night, it is unlikely to be of (straightforward) instrumental origin. The doubling makes the problem of blending among the CO lines acute. As far as possible we excluded ^{17}O and ^{18}O features which were blended by the anomalous lines (which tend to be displaced by ~ 0.09 cm^{-1} to the blue of the original line), but in the absence of any understanding of their origin, this exclusion is difficult to guarantee, and the large scatter which we found among the feature-by-feature measurements of $^{16}O/^{17}O$ and $^{16}O/^{18}O$ suggests that it may not have been achieved. The uncertainties in the ratios measured for α Ser are correspondingly larger than those for the other stars.

III. DISCUSSION

a) Effects of the Helium Core Flash on the Oxygen Isotopes

The stars in the present sample, except for β UMi, are somewhat hotter than the late-K and M type giants examined by HL1 and HL2. Their heavy-element abundances (Lambert and Ries 1981; Gratton 1985) are fairly close to the solar value $Z = 0.02$. Such stars are likely to be in one of two phases of their evolution: either at the base of the red giant branch and starting their first ascent (early stage of shell hydrogen burning) or upon the "blue loop" corresponding to the core helium-burning phase (which is of small amplitude in low-mass, high-Z stars—hence the expected early-K spectral type). In general, stars of a given mass will spend 2–10 times longer in the core He-burning phase than in the early stages of shell H burning (Faulkner and Cannon 1973; Becker 1981), giving rise to a "clump" of red giants in the color-magnitude diagrams of metal-rich star clusters at this point (Cannon 1970). The luminosities in the core He-burning stage are also higher. It is therefore probable that most early-K field giants are in the core He-burning stage rather than the early shell H-burning stage.

The helium core flash, whose effects on the oxygen isotopes we are to study, occurs in stars of $\leq 2.25\ M_\odot$ (Iben 1972). Unfortunately, it is difficult to determine the masses of the stars in our sample. We estimate the masses from the spectroscopically determined surface gravity and from the H-R diagram. In principle, perhaps, the best method exploiting the H-R diagram would be to compare a star's position with theoretical stellar evolutionary tracks for various stellar masses. However, the surface temperatures of available core He-burning models disagree with each other (see, e.g., VandenBerg 1985; Seidel, Demarque, and Weinberg 1987), and are also known to be very sensitive to the metallicity Z. It is preferable to compare observed luminosities with the model predictions, which are in good mutual agreement and are much less sensitive to Z (at least for near-solar Z-values).

In Figure 3 we show the predicted mass dependence of the luminosity during core He burning in appropriate models, and the estimated luminosities of our stars as derived from Ca II emission lines (Wilson 1976) and the trigonometric parallax (Hoffleit 1982). Wilson's tabulated absolute visual magnitudes M_V (K) were corrected for a revision of the Hyades distance modulus to $m - M = 3.23$ (see Kjaergaard *et al.* 1982; Ries 1981). Bolometric corrections were estimated from Johnson (1966) and $V-K$ colors (Johnson *et al.* 1966). Although this method is not very precise, it allows us to estimate the masses (see Table 3) of α Ari to be 1.5 $M_\odot$, that of α UMa to be $\sim 3\ M_\odot$, and that of μ Leo (Harris, Lambert, and Smith 1987) to be 1.1 $M_\odot$. Taking into account its high luminosity and low $T_{\rm eff}$, β UMi does not appear to be in the core He-burning phase at all. The low masses obtained for β Gem and α Ser suggest that these stars are ascending the giant branch as shell H-burning stars. This method applied to the Hyades giants gives $M \approx 1.6\ M_\odot$, a value close to the mass at the cluster's main-sequence turnoff ($M = 2.0 \pm 0.3\ M_\odot$; van den Heuvel 1975) and, hence, the mass of the giants in the absence of severe mass loss between the main sequence and the core He-burning stage.

TABLE 3

STELLAR MASSES (in $M_\odot$)

Star	Spectral Type	$M_{\rm He}$	M_g	$M_{\rm HR}$	$M_{\rm ad}$
β Gem	K0 III	0.5	1.3	...	1.3
α UMa	K0 II–III	3.0:	0.9	...	3.0[a]
α Ari	K2 III	1.5	0.8	...	1.0
α Ser	K2 III	0.6	1.4	...	1.4
μ Leo	K2 III	1.1	1.5	...	1.3
β UMi	K4 III	...	0.8	...	1.5
α Tau	K5 III	...	(0.2)	1.5	1.5
γ Dra	K5 III	...	0.9	...	2.0
α Boo	K2 IIIp	...	1.1	...	1.1
β And	M0 III	...	...	2.5	2.5
β Peg	M2 II–III	...	...	1.7	1.7
μ Gem	M3 III	...	...	2.0	2.0

[a] LR suggest that $M \sim 3\ M_\odot$ on the basis of α UMa's Li abundance. $M \sim 2.5$–$3.0\ M_\odot$ from the orbit of this close visual double star (see text).

An estimate of the mass is obtainable from the surface gravity (g) through the familiar relation

$$\frac{M}{M_\odot} = \frac{g}{g_\odot}\frac{L}{L_\odot}\left(\frac{T_{\rm eff,\odot}}{T_{\rm eff}}\right)^4 .$$

Lambert and Ries (1981, hereafter LR) provided estimates of g and $T_{\rm eff}$ for the stars of the present sample and others analyzed earlier. However, as discussed by them and others

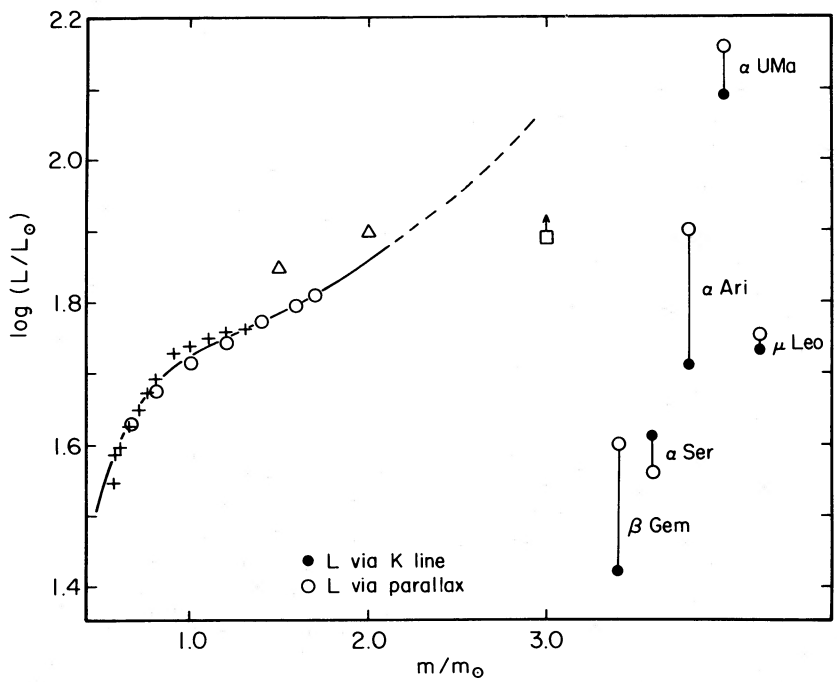

FIG. 3.—Luminosity of stars in the core helium-burning phase as a function of mass, predicted by various stellar evolution models. *Open circles:* Seidel, Demarque, and Weinberg (1987) models with $Z = 0.02$, at the midpoint of core He burning; *plus signs:* VandenBerg (1985) zero-age horizontal-branch models with $Z = 0.0169$; *triangles:* Faulkner and Cannon (1973) models ($Z = 0.02$) at the midpoint of core He burning, with core mass interpolated to 0.47 $M_\odot$; *open square:* Paczyński (1970) model with $Z = 0.03$ (arrow indicates that luminosity must be higher for a $Z = 0.02$ model comparable to the others shown). Bars at right represent observed luminosities of the labeled stars; the bars are placed at an arbitrary location along the $M/M_\odot$ axis and do not indicate the stellar mass. The luminosity is derived from Wilson's (1976) absolute visual magnitude, and from the trigonometric parallax assigned by Hoffleit (1982); see text and key on the figure.

(e.g., Kjaergaard *et al.* 1982), the $T_{\rm eff}$ values given by LR are systematically too high relative to almost all other temperature scales. Here, we correct LR's effective temperatures and surface gravities to the scales provided by Kjaergaard *et al.*: 10 stars in common give $\Delta T_{\rm eff} = T_{\rm eff}({\rm LR}) - T_{\rm eff}({\rm Kj}) = 240$ K; $\Delta \log g = \log g({\rm LR}) - \log g({\rm Kj}) = 0.32$). If two apparently discrepant points (α Ser, α Boo) are removed, the means for the remaining eight stars are $\Delta T_{\rm eff} = 270$ K and $\Delta \log g = 0.40$. Kjaergaard *et al.* obtained their estimates of g from an empirical calibration of the Ca II K line width (Lutz and Pagel 1982) based on a sample of stars with spectroscopically determined surface gravities.

As Kjaergaard *et al.* (1982) noted, their values of $T_{\rm eff}$ and g provide a mass near 2 $M_\odot$ for the Hyades giants. When the corrections, $\Delta T_{\rm eff} = 270$ K and $\Delta \log g = 0.40$, are applied to LR's values, we obtain the following masses for the four Hyades giants: $M = 1.6\ M_\odot$ (δ Tau), 2.0 $M_\odot$ (γ Tau), 1.9 $M_\odot$ (θ^1 Tau), and 1.4 $M_\odot$ (ϵ Tau) for a mean value of 1.7 $M_\odot$. The mean is increased to 2.0 $M_\odot$ when the straight mean corrections, $\Delta T_{\rm eff} = 240$ K and $\Delta \log g = 0.32$, are adopted. These values are sufficiently close to the expected mass based on the mass ($M = 2.0 \pm 0.3\ M_\odot$) at the main-sequence turnoff that we may employ the corrected LR (or Kjaergaard *et al.*'s) $T_{\rm eff}$ and g to obtain masses for our stars. Since their Li abundance is close to the predicted value for a 2 $M_\odot$ giant (Boesgaard, Heacox, and Conti 1977; Lambert, Dominy, and Sivertson 1980), we can exclude the possibility that the Hyades giants have experienced severe mass loss, and, hence, a mass near 2 $M_\odot$ is expected.

Our recipe for estimating the mass (M_g in Table 3) from LR's parameters is as follows: correct $T_{\rm eff}$ by -270 K and log g by -0.4 dex, adopt the mean absolute luminosities given by the trigonometric parallax and the (corrected) M_V(K) from Wilson (1976). For α Ser and α Boo, we adopt the $T_{\rm eff}$ and g given by Kjaergaard *et al.* (1982). With the striking exception of α Tau, the masses scatter only slightly about a mean value of 1.1 $M_\odot$. Scalo, Dominy, and Pumphrey (1978), from an analysis of visual binaries, concluded that the average mass of a red giant was $M = 1 \pm 0.2\ M_\odot$. The fact that our mean mass is within this range is additional confirmation that our treatment of the spectroscopic gravities is not vitiated by large systematic errors.

For α Tau, the mass M_g is surprisingly small. Smith and Lambert (1985) redetermine the gravity from Fe I and Fe II lines and confirm that a low gravity is provided by an LTE analysis: $\log g = 0.8$ at $T_{\rm eff} = 3850$ K (these parameters are similar to LR's after correction), and, hence, $M \sim 0.3\ M_\odot$. Smith and Lambert speculate that departures from LTE are responsible for an erroneous estimate of g. We adopt $M \sim 1.5\ M_\odot$ as estimated by Smith and Lambert from α Tau's location in the H-R diagram relative to evolutionary tracks ($M_{\rm HR}$). A similar correction is anticipated for the M_g assigned to γ Dra with, perhaps, a smaller correction for β UMi, a slightly warmer star. Mass estimates for the three M stars analyzed in HL2 are taken from Smith and Lambert (1985, 1986).

The star α UMa is a close visual binary (maximum separation ∼0″.8) with a much fainter main-sequence companion. By combining the parallax (π) provided by the absolute magnitude M_V(K) of the giant, a photoelectric estimate of the V-magnitude difference between the components ($\Delta m = 2.9$; Eggen 1955), the orbital parameters ($P = 44.66$ yr and $a =$ 0″.769) given by Couteau's (1959) fit to the double star observations, and an estimate of the fractional mass of the secondary $[m_2/(m_1 + m_2)]$ given by Spencer Jones and Furner (1938) from an analysis of meridian and double star observations, Wilson (1967) estimated the mass of the primary to be $m_1 = 2.8\ M_\odot$. When M_V(K) is taken from Wilson's later (1976) catalog and revised to a Hyades distance modulus $m - M = 3.23$ (see above), we find $\pi = 0''.040$ and $m_1 = 2.4\ M_\odot$. The parallax is in good agreement with the trigonometric parallax ($\pi = 0''.038$) given by Hoffleit (1982). Spencer Jones and Furner (1938) combined meridian, double star, and radial velocity observations to obtain $\pi = 0''.035$ and $m_1 = 2.1\ M_\odot$, in good agreement with the modern trigonometric parallax and the mass derived from Couteau's orbit.

Heintz (1963) obtained a somewhat different fit to the double star observations ($P = 44.4$ yr and $a = 0''.603$), but use of a trigonometric parallax ($\pi = 0''.031$) and the assumption that the secondary fits the M-L relation gave $m_1 = 2.4\ M_\odot$ for $\Delta m = 3.0$. The reason for the smaller semimajor axis a is unclear. If $\pi = 0''.038$ is adopted, $m_1 = 1.3\ M_\odot$ from Heintz's orbit.

Since two speckle measurements of the binary fitted Couteau's orbit rather better than Heintz's (McAlister and Hendry 1982; McAlister *et al.* 1987), we adopt $m_1 \sim 2.5$–$3.0\ M_\odot$ as the best current estimate from the double star observations. LR suggested $m \sim 3\ M_\odot$ on the basis of α UMa's Li abundance. It is clear that continued speckle observations and an accurate radial velocity curve for the primary ($K = 2.0$ km s^{-1}) could yield a more accurate estimate of the giant's mass.

Our adopted masses $M_{\rm ad}$ are given in Table 3. Of course, the uncertainties are quite large; e.g., errors of ± 100 K in $T_{\rm eff}$, ± 0.2 dex in log g, and ± 0.1 dex in $\log L/L_\odot$ added in quadrature correspond to $\Delta M \sim 0.5\ M_\odot$ for a K giant. One major conclusion seems clear: the small sample of K giants is dominated by stars that are of a sufficiently low mass ($M \leq 2.25\ M_\odot$) to experience a He core flash. As noted above, we expect a majority of these stars to be in the post–core-flash phase of core He burning. Although we are unable to identify specific candidates among our sample, it should be possible to use the oxygen isotopic abundances to test whether the He core flash leads to anomalously low abundances of ^{17}O and ^{18}O.

The isotopic ratios in Table 3 are in fact similar to the values found in most of the post–first dredge-up stars studied by HL2. In Figures 4 and 5 we plot theoretical predictions of the results of the first dredge-up for ^{16}O/^{17}O from Shadick, Falk, and Mitalas (1980) and Dearborn and Gough (1984), and for ^{16}O/^{18}O from HL1 and HL2, as a function of mass. The observed ratios from HL1, HL2, and the present work are also plotted. For completeness we also show the predicted results for ^{16}O/^{17}O of the second dredge-up, which is expected to occur at the end of core He burning in stars of $\gtrsim 5\ M_\odot$, from HLS (its effect on ^{16}O/^{18}O is expected to be negligible for most stars). The masses of α Her, α Ori, and α Sco are taken to be 7, 15, and 15 $M_\odot$, respectively (HL1, HL2).

From Figure 4 we see that the observed ^{16}O/^{17}O ratio in stars with $M \lesssim 2\ M_\odot$ is systematically below the predictions. It is just this sample that is expected to include those He core burning giants that experienced a He core flash. However, it is premature to identify mixing at the core flash as the sole source of the excess ^{17}O in these giants. We cannot exclude mixing in either the main-sequence or subgiant progenitors as contributors to the ^{17}O overabundance. A systematic underestimate of the stellar masses by about 50% might also be responsible for the displacement of the observed parts in Figure 4 from the

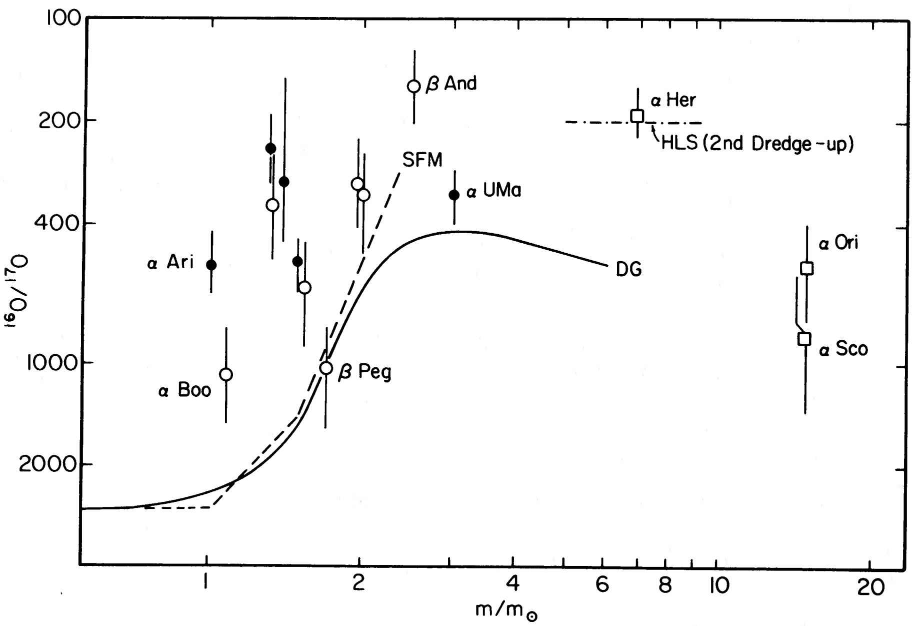

FIG. 4.—Predicted and observed $^{16}O/^{17}O$ ratios as a function of stellar mass. First dredge-up predictions are labeled *SFM* (*dashed line;* Shadick, Falk, and Mitalas 1980) and *DG* (*solid line;* Dearborn and Gough 1984). The second dredge-up prediction by HLS is shown by the dot-dash line. Ratios measured in this paper are represented by filled circles. Results from HL1 and HL2 are represented by the open symbols (*circles:* giants; *squares:* supergiants). Selected stars are identified by name.

predicted lines. Moreover, the rates for destruction of ^{17}O by protons are subject to such uncertainties that the location of the predicted line may itself be in error by a significant amount. From Figure 5 we see that all the stars with measured $^{16}O/^{18}O$ ratios are in good agreement with the first dredge-up predictions; ^{18}O is depleted only slightly in all red giants.

Although the precise evolutionary stage of the lower mass stars is uncertain, we may conclude with fair confidence that several stars must have experienced a violent He core flash. Since none of the stars have remarkably low abundances of either ^{17}O or ^{18}O, we conclude that the He core flash is not responsible for the anomalously low abundances of ^{17}O and ^{18}O seen in the AGB stars.

On the contrary, one might argue on the basis of Figure 4 that the He core flash has led to a modest enhancement of the ^{17}O abundance, but no significant change of the ^{18}O abundance (see Fig. 5). These changes are not unexpected. It is well known that the first dredge-up penetrates to layers of the stellar interior in which the ^{17}O abundance (enhanced by the CNO cycle) is increasing radially inward at a very steep rate (see, for example, Fig. 3 of HL2, point labeled M_D). Therefore, only a small further penetration by the convective envelope due to the He core flash is needed to bring about a large enhancement of ^{17}O. (The required penetration may also be achieved before and after the core flash.) Such a small further advance would not materially affect the abundances of the other nuclei involved in the CNO cycle—at most one would expect a small ($\ll 0.3$ dex) enhancement of ^{14}N, the only other nucleus overproduced in these layers. This explains why, while the $^{16}O/^{17}O$ ratio is much smaller than expected, the $^{16}O/^{18}O$

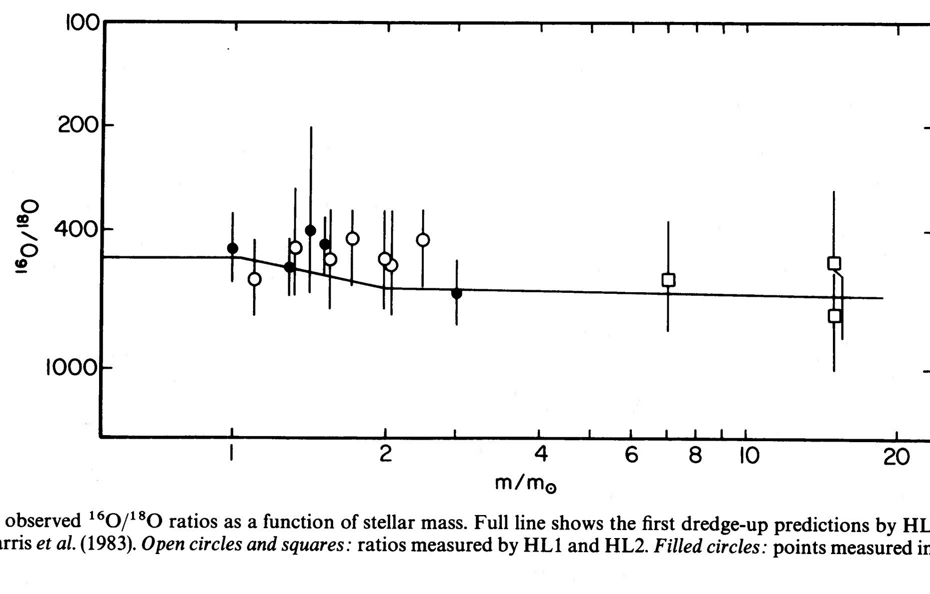

FIG. 5.—Predicted and observed $^{16}O/^{18}O$ ratios as a function of stellar mass. Full line shows the first dredge-up predictions by HL1 and HL2 using the "low" rate for $^{18}O(p, \alpha)^{15}N$ of Harris *et al.* (1983). *Open circles and squares:* ratios measured by HL1 and HL2. *Filled circles:* points measured in this paper.

ratio remains at the post–first dredge-up level, as do the abundances of the other CNO-cycle nuclei according to Lambert and Ries (1981) and Gratton (1985). The proposal also explains why the $^{16}O/^{17}O$ and $^{12}C/^{13}C$ ratios are uncorrelated.

A small further penetration of the convective envelope (under the sobriquet "extramixing") is in fact predicted by the most sophisticated models of the helium core flash (Deupree and Cole 1983). It is not expected to change the gross features of a star's postflash evolution (Seidel, Demarque, and Weinberg 1987). Presumably this extramixing ought to be more pronounced in the stars of lower mass, which experience a more violent flash. Such a speculation may account, as the referee noted, for the fact that many metal-poor red giants possess very low $^{12}C/^{13}C$ ratios (Sneden, Pilachowski, and VandenBerg 1986).

b) *Status of the AGB Oxygen Isotope Problem*

Of the four possible explanations proferred by HLS for the anomalously high oxygen isotope ratios in AGB stars, three have subsequently been discarded. The first hypothesis (an increase in the ratios due to the addition of ^{16}O synthesized during shell He burning) was rejected by HLS because the ^{16}O in these stars is not enhanced above its solar abundance (Smith and Lambert 1985, 1986; Lambert *et al.* 1986). The second explanation (high values of $^{16}O/^{17}O$ are retained from the star's birth if its mass is low [cf. Fig. 4], and ^{18}O is destroyed by the $^{18}O(p, \alpha)^{15}N$ reaction) has been disproved by Champagne and Pitt's (1986) measurement of a low rate for the $^{18}O(p, \alpha)$ reaction. The third proposal (destruction of ^{17}O and ^{18}O in the He core flash) has been dealt with above.

This leaves the suggestion that the ^{17}O and ^{18}O abundances in the envelopes of AGB stars are diluted by the dredge-up of material devoid of ^{17}O and ^{18}O, such as is expected to subsist in the helium-burning shell in these stars. This hypothesis is qualitatively, but not quantitatively, compatible with current models of the helium shell flash (thermal pulse) phenomenon and the third dredge-up (Iben and Renzini 1983). For such a dilution effect to be significant, the amount of material brought up by the succession of third dredge-ups must be comparable to, or greater than, the mass of the star's envelope. However, stellar evolution models predict that the mass brought up by all the third dredge-ups ($\sim 0.1\ M_\odot$) is much smaller than the envelope mass ($\sim 1\ M_\odot$). Either the envelope mass has to be radically reduced by mass loss, or the amount of mass dredged up must be greater than predicted (or both) if the oxygen isotope ratios are to be explained by this mechanism. This dilution hypothesis also predicts much higher ^{12}C and lower ^{16}O abundances than these stars are observed to have at their surfaces, although a recent upward revision of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate (Kettner *et al.* 1982; Redder *et al.* 1987) may resolve the discrepancy. The dilution hypothesis does explain in a natural way the discovery of HLS and Harris *et al.* (1987) that the anomalous depletions of ^{17}O and ^{18}O are correlated with the neutron exposure parameter τ_0 of the *s*-process elements observed in these stars. The *s*-process is thought to advance in exposure at each succeeding shell flash (Ulrich 1973), and the dilution of ^{17}O and ^{18}O also proceeds as more and more He shell material is added and more and more envelope mass is lost.

The suggestion that the AGB stars' envelopes are reduced by mass loss is an attractive one, in the light of an apparent contradiction between the oxygen isotope ratios observed in barium stars (Harris, Lambert, and Smith 1985*a*) and in single AGB stars. Barium stars may arise from the tranfer of mass from the envelope of an AGB star to a less evolved binary companion (the future barium star, which is seen after the AGB star has evolved to a white dwarf). Evidence for such an origin of barium stars is reviewed by Lambert (1985); here we will consider the behavior of the oxygen isotopes.

Harris, Lambert, and Smith (1985*a*) showed that the oxygen isotope ratios in barium stars agree with the predictions of the mass transfer model *if the AGB star has the low oxygen isotope ratios theoretically expected* (these are $^{16}O/^{17}O \sim 200$ and either $^{16}O/^{18}O \sim 600$ or $^{16}O/^{18}O \sim 100$, according to HLS). The fact that most AGB stars have ratios $^{16}O/^{17}O$ and $^{16}O/^{18}O \gtrsim 1000$ appears to destroy any possibility that barium stars have accreted material from their envelopes. However, the low ratios inferred from barium stars are actually expected, if the high ratios in the "parent" AGB stars are due to reduction of the envelope by mass loss.

To see why this is so, note that we see a barium star at a time when it has finished accreting the AGB parent's envelope. If $\sim 0.1\ M_\odot$ in total was brought up to a 1 $M_\odot$ envelope by the third dredge-ups in the AGB star, and if this material was devoid of ^{17}O and ^{18}O, the overall dilution factor of the ^{17}O and ^{18}O abundances in the transferred material is 1.0/1.1. In other words, the barium star receives material in which the ^{17}O and ^{18}O abundances are not heavily diluted *overall*. The material received in the later stages of mass loss, when the AGB parent's envelope was reduced in mass to $\sim 0.1\ M_\odot$, would have its ^{17}O and ^{18}O content heavily diluted, but, overall, this later-arriving material makes little contribution to the barium star. However, it is in these later stages (by hypothesis) that we see single AGB stars today, and hence, we see heavily diluted ^{17}O and ^{18}O abundances.

IV. CONCLUSIONS

We conclude that the helium core flash is not responsible for the very high $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios found in stars in later (AGB) stages of evolution. Our measurements tend to confirm the extramixing predicted to result from the helium core flash, which reduces $^{16}O/^{17}O$ and leaves $^{16}O/^{18}O$ essentially unchanged relative to their post–first dredge-up values.

These conclusions would be fortified by measurements of the oxygen isotope ratios in a larger sample of early-K giants. While there is no technical obstacle to making such measurements from 5 μm spectra, interpretation is hampered by the difficulty of assigning masses to the stars involved (and thereby selecting those which are likely to have undergone the He core flash). Improved stellar evolution model sequences for the core He-burning stage, combined with more accurate observational determinations of stellar temperatures (and even luminosities), would go far toward solving this problem. Better models of the effect of the first and second dredge-ups on the $^{16}O/^{17}O$ ratio would also aid interpretation (note the discrepancies between the two first dredge-up models in Fig. 4, and the uncertainty expressed by HLS over their second dredge-up prediction).

We also conclude that the anomalous oxygen isotope ratios in AGB stars are due to the dilution of the ^{17}O and ^{18}O abundances in their envelopes by the dredge-up of material in which ^{17}O and ^{18}O have been destroyed by shell He burning. Stellar evolution models of AGB stars, including a treatment of mass loss, an updated $^{12}C(\alpha, \gamma)^{16}O$ nuclear reaction rate, and a reaction network including the minor oxygen isotopes would allow a quantitative attack on a problem which we have been obliged here to treat qualitatively. Independent measurements of the oxygen isotope ratios in AGB stars, as performed by Dominy and Wallerstein (1987) for $^{16}O/^{17}O$, are also, of course, desirable.

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