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OXYGEN ISOTOPIC ABUNDANCES IN THE ATMOSPHERES OF SEVEN RED GIANT STARS

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ABSTRACT

Abundance ratios of the oxygen isotopes have been measured in α Tau, β And, μ Gem, α Her, β Peg, γ Dra, and α Boo. In all the stars the $^{16}O/^{18}O$ ratios are similar; the mean value is 475, which is consistent with the solar system value $^{16}O/^{18}O = 490$. The $^{16}O/^{17}O$ ratios range from ~1000 for β Peg and α Boo to $^{16}O/^{17}O = 160$ for β And.

Standard descriptions of stellar evolution predict that a red giant's convective envelope will dredge up material processed slightly by CNO-cycle nuclear reactions during the main-sequence phase. The $^{16}O/^{18}O$ ratios and previously reported $^{12}C/^{13}C$ ratios suggest that the standard description must be modified in at least two ways. First, the rate of the $^{18}O(p, \alpha)^{15}N$ reaction must be reduced to near the minimum value allowed by experiment. Second, a slow mixing of the outer layers must occur during the main-sequence phase enabling more ^{13}C to be produced. Mass loss prior to the dredge-up is an additional possibility but is excluded for most of the stars by the observed high lithium and ^{18}O abundances.

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

I. INTRODUCTION

Both theoretical arguments (Iben 1967) and observations (Lambert 1981) indicate that on joining the red giant branch all stars undergo a dredge-up process which brings to the surface material which underwent CN-cycle reactions during the preceding main-sequence evolution. The stars' atmospheres are thus enriched in, for example, ^{13}C and ^{14}N. Unfortunately, the standard stellar evolution models of single nonrotating mass-conserving stars tend to predict $^{12}C/^{13}C$ ratios that are too large, being ~20 or greater, whereas observed ratios may be as low as 6. Observations of other nuclei undergoing nuclear reactions at CN-cycle temperatures may suggest how the standard models must be modified to resolve this discrepancy.

In a previous paper (Harris and Lambert 1984, hereafter HL) we have shown how measurements of ^{17}O and ^{18}O abundances in the red supergiants α Ori and α Sco may constrain explanations of the low $^{12}C/^{13}C$ ratios observed in these stars. Here we extend the analysis to seven other red giants of lower mass. These stars cover a range of spectral types from K1 to M5, and include the metal-poor low-mass object α Boo. They are all assumed to be ascending the red giant branch for the first time, so that for most of them the dredge-up referred to above is the only event since birth to have affected their surface abundances. The exception is α Boo, for which a shell-flashing mechanism has been proposed, which we discuss in § V. Stars of between 3 and 8 $M_\odot$ are expected to undergo a second dredge-up at the beginning of their second ascent of the red giant branch. However, the lifetime of stars on their second ascent prior to the onset of helium shell flashing is expected to be about an order of magnitude less than the lifetime on the first ascent (Becker and Iben 1980; Becker 1981), so that few of the stars on the red giant branch are expected to be in this stage of evolution. The second dredge-up is not expected to alter $^{12}C/^{13}C$ or $^{16}O/^{18}O$ ratios at the surface (Iben and Truran 1978).

Several narrow windows near 5 μm allow observations of the fundamental vibration-rotation lines of the CO molecule in its ground electronic state. Absorption lines in the 5 μm region include lines from the different isotopic species of CO. Spectra of the first-overtone bands at 2.3 μm provide weaker $^{12}C^{16}O$ and $^{13}C^{16}O$ lines. Considerably weaker lines of $^{12}C^{17}O$ are also visible around 2.3 μm, from which Maillard (1974) deduced a $^{16}O/^{17}O$ ratio of ~450 in α Her, compared with a value of $\sim 500^{-250}_{+1000}$ obtained by Geballe *et al.* (1977) from the 5 μm region. Geballe *et al.* also obtained a lower limit of 500 for the $^{16}O/^{18}O$ ratio in this star. Oxygen isotopic ratios have not been reported previously for any other stars in our group of seven.

II. OBSERVATIONS

The stars which we have studied are listed in Table 1. The 5 μm spectra were obtained from the KPNO archives, having been taken at the coudé focus of the 4 m telescope with the Fourier transform spectrometer (FTS). A comparison spectrum of Mercury, taken with the same instrument, was used to "ratio out" telluric lines, in the manner described by HL. By adjusting the air-mass ratio in Beer's law for ratioing spectra, it was found that virtually all telluric lines could be satisfactorily removed.

As noted in HL, an intensity modulation arises in these spectra as a result of a defect in the FTS beam splitter, having an amplitude of ~10% and a wavelength of ~15 cm $^{-1}$, which it was not found possible to remove. The error thus introduced into the intensity of a given spectral feature is random, and a sufficiently large number of features were observed in all stars that an average result should be reliable. The broad filter employed introduces a modulation of longer wavelength, which was removed wherever possible by dividing the spectrum by a smoothed spectrum of a soldering iron taken with the same filter. Such an iron spectrum was available for all the stars observed except γ Dra.

Windows in the telluric absorption were identified between 2132 and 2162 cm^{-1} for all the stars. In the case of γ Dra a

TABLE 1

JOURNAL OF OBSERVATIONS

Object	Date	Spectral Region (cm^{-1})	Apodized Resolution (cm^{-1})	Integration Time (s)
γ Dra	1979 May 14	1896.9–2334.6	0.068	7095
β Peg	1979 Dec 2	1969.8–2261.6	0.017	8707
μ Gem	1980 Jan 5	1969.8–2261.6	0.017	4199
β And	1980 Feb 5	1896.9–2334.6	0.034	1879
α Tau	1980 Feb 6	1969.8–2261.6	0.017	2554
α Her	1980 Feb 6	1969.8–2261.6	0.017	2867
α Boo	1980 Feb 6	1969.8–2261.6	0.017	4324
Mercury	1979 Mar 6	1896.9–2334.6	0.034	1084

broader filter allowed the use of windows between 2000 and 2162 cm^{-1}.

Spectra of α Her, α Tau, β And, and γ Dra in the 2.3 μm window were taken at KPNO with the FTS (Smith and Lambert 1984). Spectra at 2.3 μm of the other stars were retrieved from the KPNO archive and measured by Dominy, Hinkle, and Lambert (1984) as part of a survey of the $^{12}C/^{13}C$ ratios in red giants.

III. ANALYSIS AND RESULTS

Our analysis based on a comparison of synthetic and observed spectra was described by HL. Spectra were synthesized with the program MOOG (Sneden 1974), using a CO line list obtained from the molecular constants of Dale *et al.* (1979); the *gf*-values used were obtained from Chackerian and Tipping (1983). Very few lines due to atomic transitions or to molecules other than CO are present at 5 μm. Large numbers of lines due to species containing ^{17}O and ^{18}O were observed (see Table 2); in most cases they were blended with other CO lines, as are nearly all lines in this region.

Effective temperatures and gravities for these stars were taken from Dominy, Hinkle, and Lambert (1948). The model atmospheres used in the syntheses were taken from Bell *et al.* (1976) (generally for stars with $T_{\rm eff} > 3800$ K) and from Johnson, Bernat, and Krupp (1980) for cooler stars. The Bell *et al.* models were interpolated to the exact values of $T_{\rm eff}$ and log g; for the cooler stars the closest model in the Johnson, Bernat, and Krupp grid of models was employed. In all cases except α Boo models computed on the basis of solar system abundances were used (for α Boo the model used assumed a metallicity of -0.6 dex).

The major problem in comparing the synthetic and observed spectra is that at 5 μm the apparent continuum drops below the true continuum (i.e., that in the absence of lines) as a result of the high incidence of blending and the overlapping of line wings. We adopted the same procedure as in HL to determine the true continuum level; a $^{13}C^{16}O$ abundance was assumed for each star, and observed weak $^{13}C^{16}O$ lines were matched to the lines synthesized using this abundance. The assumed $^{13}C^{16}O$ abundances were obtained from the $^{12}C/^{13}C$ ratios measured by previous authors and from the elemental carbon abundances necessary to fit weak $^{12}C^{16}O$ lines at 1.6, 2.3, and 5 μm (see Table 2). Strong CO features (i.e., intensity levels more than 40% below the continuum) were disregarded in fitting the synthetic to the observed spectra, since the absorption at such points arises from layers high in the atmosphere, in which the model atmospheres are unreliable because of the presence of chromospheres, mass motions, and so on.

Initial estimates of the microturbulent velocities ξ were taken from Dominy, Hinkle, and Lambert's (1984) analysis of first- and second-overtone lines. These estimates were used as starting points for our own estimates (Table 3) based on intermediate-strength features of $^{12}C^{16}O$ and $^{13}C^{16}O$. Macroturbulent velocities Γ were also introduced, ξ and Γ being adjusted together until the profiles of the features mentioned above and of the few unblended lines were satisfactorily reproduced.

The abundances of ^{17}O and ^{18}O in the synthetic spectrum were adjusted, feature by feature, until the best fit to each of the features due to one or both species was achieved. The mean of these best-fitting abundances, weighted in the manner described in HL to take account of degree of blending, intrinsic strength, and reliability of the continuum determination, is presented in Table 3 as the 5 μm result for each star. The major contributions to the error estimates in Table 3 arise from the internal dispersion in the abundances derived from the features (which is probably largely due to the modulation described in § II) and from the uncertainty in the assumed $^{12}C/^{13}C$ ratio,

TABLE 2

INPUT PARAMETERS FOR ABUNDANCE ANALYSIS

			MODEL			$^{12}C/^{13}C$			NUMBER OF FEATURES		
OBJECT	$T_{\rm eff}$	log g	Source	$T_{\rm eff}$	log g	Source	Ratio	[C]	^{17}O	^{18}O	$^{17}O + ^{18}O$
α Boo	4375	1.57	1	4375	1.57	3	7 ± 1.5	-0.70	15	16	5
α Tau	3831	1.41	2	3800	1.50	4	9 ± 1	-0.30	21	16	2
β And	3726	1.84	1	3726	1.84	5	11 ± 1.5	-0.30	20	15	2
μ Gem	3583	1.21	2	3600	1.00	6	13 ± 2	-0.30	21	13	1
α Her	3332	1.00	2	3400	1.00	3	17 ± 4	0.0	19	22	2
β Peg	3568	1.66	2	3600	1.50	3, 7	7 ± 1	0.0	22	16	6
γ Dra	3980	1.87	1	3980	1.87	4	13 ± 2	-0.25	20	14	4

SOURCE.—(1) Bell *et al.* 1976. (2) Johnson, Bernat, and Krupp 1980. (3) Hinkle, Lambert, and Snell 1976. (4) Tomkin, Lambert, and Luck 1975. (5) Tomkin, Luck, and Lambert 1976. (6) Dominy, Hinkle, and Lambert 1984. (7) Smith and Lambert 1984.

TABLE 3

ISOTOPIC ABUNDANCES

Object	ξ (km s^{-1})	Γ (km s^{-1})	$^{16}O/^{17}O$	References	$^{16}O/^{18}O$	References	$^{17}O/^{18}O$	References
α Boo	1.6	4.0	1100^{-300}_{+400}	1	550^{-125}_{+150}	1	0.5 ± 0.1	1
			~ 2000	2	$\gtrsim 300$	2		
α Tau	2.0	1.5	600^{-150}_{+300}	1	475^{-125}_{+200}	1	0.75 ± 0.25	1
			525^{-125}_{+250}	2	~ 500	2		
β And	1.6	3.5	155^{-30}_{+50}	1	425^{-75}_{+150}	1	2.8 ± 0.4	1
			170 ± 10	2	400^{-150}_{+600}	2	$2.4^{-1.0}_{+2.5}$	2
μ Gem	2.5	2.0	325^{-75}_{+150}	1	475^{-125}_{+200}	1	$1.4^{-0.3}_{+0.4}$	1
			$\gtrsim 100$	2	$\gtrsim 500$	2		
α Her	3.0	3.0	180^{-50}_{+70}	1	550^{-175}_{+225}	1	3.0 ± 0.6	1
			200 ± 25	2	~ 700	2	~ 3.5	2
			~ 450	3				
			500^{-250}_{+1000}	4				
β Peg	2.0	3.0	1050^{-250}_{+500}	1	425^{-75}_{+150}	1	0.4 ± 0.1	1
			$\gtrsim 100$	2	$\gtrsim 100$	2		
γ Dra	2.0	6.0	300^{-75}_{+100}	1	500^{-150}_{+200}	1	1.75 ± 0.25	1
			$\gtrsim 250$	2	$\gtrsim 200$	2		
α Ori	...	...	525^{-125}_{+250}	5	700^{-175}_{+300}	5	1.3 ± 0.3	5
α Sco	...	...	850^{-300}_{+550}	5	500^{-200}_{+300}	5	0.6 ± 0.2	5
Solar	...	...	2630	6	490	6	0.186	6

REFERENCES.—(1) This paper, 5 μm spectra. (2) This paper, 2.3 μm spectra. The error estimates include internal dispersion only. (3) Maillard 1974. (4) Geballe *et al.* 1977. (5) Harris and Lambert 1984. (6) Anders and Ebihara 1982.

which directly affects our location of the continuum as described above, and as noted in HL is linked to uncertainties in our estimates of ξ and Γ. Errors due to the uncertainties in the model atmospheres and effective temperatures were found to be small ($\sim 5\%$ in each case). This is to be expected, since we are comparing $C^{17}O$ and $C^{18}O$ lines with $^{12}C^{16}O$ and $^{13}C^{16}O$ lines of similar excitation potential and intensity. In the case of γ Dra the rather poor resolution (Table 1) introduces an additional uncertainty, which is also included in the error estimate. Figures 1 and 2 show sample comparisons of observed and synthetic spectra; note the presence of several $^{12}C^{16}O$ and $^{13}C^{16}O$ lines with intensities similar to those of $C^{17}O$ and $C^{18}O$ features.

The 2.3 μm spectra were examined to check the ^{17}O and ^{18}O abundances wherever possible. For μ Gem, β Peg, and γ Dra no lines due to either species were detected, and only upper limits on their abundances can be estimated. In α Her, α Tau, and β And very weak $^{12}C^{18}O$ lines were detected (one in the first two, three in the last) from which $^{16}O/^{18}O$ ratios of ~ 700, 500, and 400, respectively, were deduced by spectrum synthesis fits. However, in these three stars several lines of the 2–0 band of $^{12}C^{17}O$ between 4269 and 4294 cm^{-1} were observed (for α

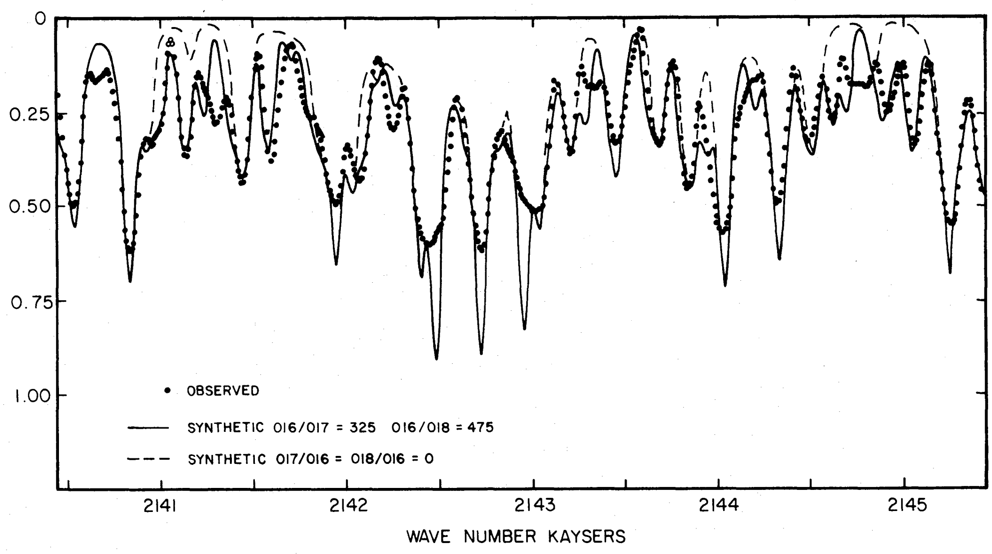

FIG. 1.—Comparison of selected observed and synthesized spectra for μ Gem

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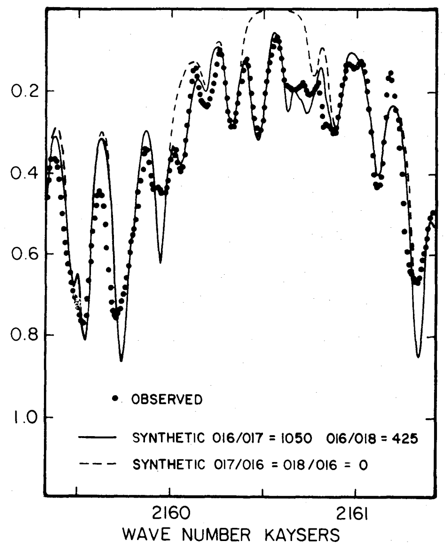

FIG. 2.—Comparison of selected observed and synthesized spectra for β Peg.

Her nine lines between R20 and R33, for α Tau four lines between R27 and R33, and for β And six lines between R21 and R32 and four weak lines between R69 and R73), from which $^{16}O/^{17}O$ ratios were derived. As seen in Table 3, they are in very good agreement with the 5 μm results for these stars. In α Boo no $^{12}C^{18}O$ lines were detected, and one very weak $^{12}C^{17}O$ line yielded a very approximate ratio of $^{16}O/^{17}O \approx 2000$.

Maillard (1974) first exploited the presence of these unblended 2–0 *R*-branch lines of $^{12}C^{17}O$. Our result for α Her differs from his by more than a factor 2, probably because of the simple one-zone atmosphere Maillard used and because his assumed effective temperature of 2950 K was unjustifiably low. A similar choice of too low an effective temperature (3000 K) may also explain the similar discrepancy between our result for α Her and that of Geballe *et al.* (1977).

IV. ENVELOPE CNO ABUNDANCES AFTER THE FIRST DREDGE-UP

a) *Predictions: Quantitative and Qualitative*

Standard stellar evolutionary models by Dearborn, Eggleton, and Schramm (1976), Dearborn, Tinsley, and Schramm (1978), Dearborn and Gough (1984), and Shadick, Falk, and Mitalas (1980) predict the ratios $^{12}C/^{13}C$ and $^{16}O/^{17}O$ after the first dredge-up at the base of the red giant branch, as functions of stellar mass. Qualitatively, they predict $^{12}C/^{13}C$ ratios declining from an initial value of 89 (the solar system ratio) to ~ 30 for 1 $M_\odot$ stars and ~ 25 for 5 $M_\odot$ stars. Observations of interstellar molecular lines suggest that $^{12}C/^{13}C \approx 60$ in the local gas (Wannier 1980). The predicted $^{12}C/^{13}C$ ratios for red giants are insensitive to a change in the initial ratio from 89 to near 60. For stars of ~ 1 $M_\odot$ or less the dredge-up is not predicted to decrease $^{16}O/^{17}O$ (Dearborn, Bolton, and Eggleton 1975, hereafter DBE), but above this mass $^{16}O/^{17}O$ will decrease steadily until a mass 2–3 $M_\odot$, above which it will remain constant at a value which differs in different models, in the range 250–600. The $^{16}O/^{18}O$ ratio is predicted to increase as $^{12}C/^{13}C$ decreases: if the initial value is the solar system ratio $^{16}O/^{18}O = 490$, the predicted post–dredge-up ratios are 610 for 1 $M_\odot$ stars and 950 for 5 $M_\odot$ stars. These figures are provided by Dearborn, Tinsley, and Schramm (1978); other calculations confirm the trends of these predictions but offer some quantitative differences. The differences reflect a variety of factors: different assumptions about the initial abundances, differing treatments of convection, mass loss, and so on. As the observational results on the composition of red giants become more comprehensive and more accurate, there is a need for full evaluation of the uncertainties in these predictions.

As an aid to the interpretation of our results, we present in Figure 3 an approximation of the abundance profile inside a 2 $M_\odot$ model at the end of main-sequence evolution, just before the dredge-up (from Dearborn, Eggleton, and Schramm 1976). The full lines represent the abundances expected from this standard model. Three key points may be derived from these abundances. First, there is a large zone just below the point $M(r) = 1.0$ in which ^{13}C is strongly enhanced, which causes the $^{12}C/^{13}C$ ratio to decrease sharply when the red giant's convective envelope dredges up material as far down as the point M_D. However, many red giants, including most of our sample, show a $^{12}C/^{13}C$ ratio below the values predicted by such a model. Two direct modifications of the standard models to explain these lower $^{12}C/^{13}C$ ratios are (i) mass loss prior to the end of main-sequence evolution, which reduces the amount of the low ^{13}C envelope above $M(r) = 1.0$ mixed with the high ^{13}C

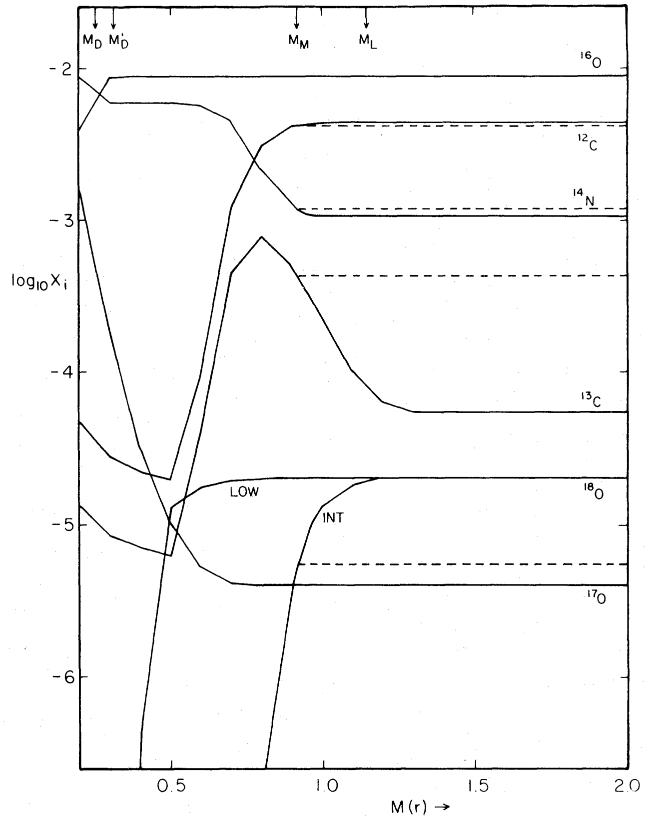

FIG. 3.—Approximation to the structure of a 2 $M_\odot$ star at a time near the end of main-sequence evolution, from Dearborn, Eggleton, and Schramm (1976). Full lines indicate the abundances of labeled isotopic species according to this model. Arrows locate the values of the parameters introduced in order to explain the $^{12}C/^{13}C$ and $^{16}O/^{17}O$ ratios in α Tau: M_D and M_D' the dredge-up depths in the mixing and mass-loss cases, respectively; M_M the depth to which the envelope is assumed to be mixed in the mixing case; M_L the surface of the star after the mass loss in the mass-loss case. Dashed lines indicate the isotopic abundances resulting from the envelope being mixed down to M_M throughout main-sequence evolution.

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material below, and (ii) an internal mixing which circulates material in the outer envelope through a deeper, hotter layer [point $M(r) = M_M$], so that the envelope acquires a high ^{13}C abundance characteristic of that layer before the dredge-up (see the dashed line in Fig. 3).

Second, the ^{17}O abundance is enhanced only in the deepest layers reached by the dredge-up, around point M_D, but in these layers the enhancement is very large. It follows that the ^{16}O/^{17}O ratio after dredge-up is very sensitive to the precise value of M_D, and that it is virtually decoupled from the abundances of the other species, which are abundant much higher up, since very small changes in M_D will produce large changes in the ^{17}O abundance but very little change in the other abundances. Since the ^{17}O-rich layer incorporated into the convective envelope is so thin, mass loss prior to the end of main-sequence evolution must be extremely severe in order to significantly affect the final ^{16}O/^{17}O ratio. Likewise, the postulated mixing will have very little effect on the ^{16}O/^{17}O ratio since it is confined to layers in which the temperature is too low for ^{17}O to be enhanced (Fig. 3). In sum, the ^{16}O/^{17}O ratio only contains information on the depth M_D of the red giant's convective envelope and cannot be used to constrain explanations of the low ^{12}C/^{13}C ratios.

Third, ^{18}O is not produced by any reaction in the CNO cycles, but is destroyed by ^{18}O(p, α)^{15}N, whose rate is very uncertain. The standard models use a value close to the "intermediate" rate recommended by Harris *et al.* (1983), which leads to ^{18}O being depleted throughout most of the ^{13}C-rich region (Fig. 3, curve labeled "INT"). Therefore, low ^{12}C/^{13}C ratios should always be accompanied by high ^{16}O/^{18}O ratios, and the modifications above designed to produce even lower ^{12}C/^{13}C ratios will cause even higher ^{16}O/^{18}O ratios. However, if the ^{18}O(p, α) rate is close to (or below) the lower limit set by Harris *et al.*, ^{18}O avoids destruction down to depths well below the ^{13}C-rich zone (Fig. 3, curve labeled "LOW"). In this latter case, mixing of the envelope of the main-sequence star down to layer M_M will leave the ^{16}O/^{18}O ratio virtually unaffected, since the temperature at point M_M is not high enough to destroy either ^{16}O or ^{18}O. Main-sequence mass loss, however, will cause an increase in ^{16}O/^{18}O, since less envelope material rich in ^{18}O will be mixed with the ^{18}O-poor layers close to point M_D. The ^{16}O/^{18}O ratio may therefore shed light on which of these two processes better explains the low ^{12}C/^{13}C ratios. It may also be noted that (unlike ^{13}C and ^{17}O) ^{18}O is sensitive to the initial ^{18}O abundance at the star's birth.

In the following sections we sketch how the standard models might be modified to fit the observed ^{12}C/^{13}C, ^{16}O/^{17}O, and ^{16}O/^{18}O ratios (Tables 2 and 3). We shall also consider the key elemental abundance ratio ^{12}C/^{14}N, which is also affected by the mass-loss and mixing modifications outlined above, but is unfortunately less well known. We shall consider α Boo separately from the other stars since a different mechanism has been proposed to explain its ^{12}C/^{13}C ratio (see § V).

b) The ^{12}C/^{13}C *and* ^{16}O/^{18}O *Ratios*

Our discussion of the abundance profiles in a 2 $M_\odot$ main-sequence star (Fig. 3) emphasized that, if the ^{18}O(p, α) reaction rate hitherto recommended is correct, the ^{12}C/^{13}C and ^{16}O/^{18}O ratios should be anticorrelated. The observations show no such trend (Fig. 4). The ^{16}O/^{18}O ratios appear to be remarkably similar for all stars; ^{16}O/^{18}O = 475 ± 40 is the weighted mean for the six stars considered here. If the supergiants α Ori and α Sco discussed by HL are included the mean ratio becomes 500 ± 80. The solar system ratio is ^{16}O/^{18}O = 490; recent reviews of abundances in the interstellar medium give values 500 ± 50 (Wannier 1980) and 675 ± 200 (Penzias 1981). Within its uncertainties, our mean ^{16}O/^{18}O ratio for the giants and supergiants is identical with these ratios, which probably represent the stars' initial ^{16}O/^{18}O ratios. This coincidence and the narrow range of ^{16}O/^{18}O ratios exhibited by stars spanning a factor of 4 range in their ^{12}C/^{13}C ratios point to the conclusion that ^{18}O survives destruction by ^{18}O(p, α) down to depths beyond the ^{13}C peak in main-sequence stars of masses between 1 and 15 $M_\odot$. This requirement can be met only if the ^{18}O(p, α) reaction rate is set at or below the minimum value (the "low" rate) proposed by Harris *et al.*, (1983). This fortifies the same conclusion reached by HL.

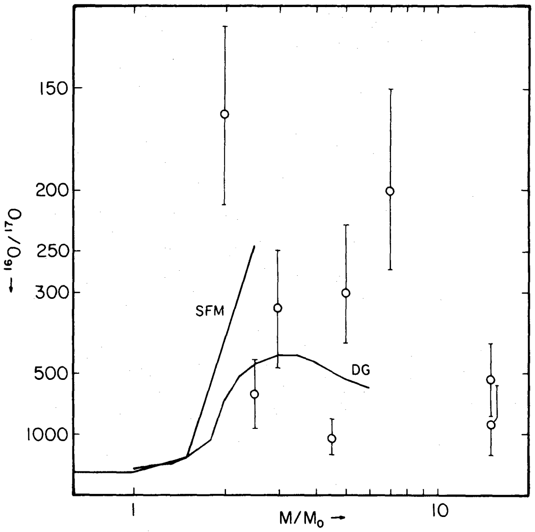

FIG. 4.—The ratio ^{16}O/^{18}O as a function of ^{12}C/^{13}C for the stars studied in this paper and in HL, apart from α Boo. Full line is the relation expected from the standard stellar evolution models of Dearborn, Tinsley, and Schramm (1978). Dashed line illustrates the effect on the ratios of severe mass loss, as approximated by HL.

A quantitative exploration of the effects of mass loss and internal mixing prior to the end of main-sequence evolution was made for the six stars in the present sample. Unfortunately none of them has a reliably determined mass. Tsuji (1981) has estimated masses for several of them on the basis of evolutionary tracks by Paczyński (1970), concluding that α Tau, β And, and μ Gem have masses in the range 2–3 $M_\odot$, β Peg is ~5 $M_\odot$, and α Her is ~7 $M_\odot$. We find very similar values on the basis of temperatures and luminosities from Dominy, Hinkle, and Lambert (1984) and evolutionary tracks by Becker (1981); on the same basis we estimate that γ Dra has a mass of ~5 $M_\odot$. The mass of β Peg is especially uncertain, with estimates ranging from less than 2 $M_\odot$ according to the Wilson-Bappu effect (Wilson 1976) to 10 $M_\odot$ (from Dominy, Hinkle, and Lambert 1984). An intermediate value of 5 $M_\odot$ has been adopted here. Since detailed descriptions of stellar models of 2 and 5 $M_\odot$ have been published, we have used these in our calculations.

The 2 $M_\odot$ model of Dearborn, Eggleton, and Schramm (1976) (for α Tau, β And, and μ Gem) and the 5 $M_\odot$ model of Iben (1967) (for α Her, β Peg, and γ Dra) were adapted to approximate the effects of mass loss and of the postulated

TABLE 4

COMPARISON WITH STELLAR EVOLUTION MODELS

OBJECT	MODEL	M_D	M_M	M_D'	M_L	$^{16}O/^{18}O$ (low)			$^{16}O/^{18}O$ (internal)			$^{12}C/^{14}N$		
						Mixing	Mass Loss	Observed	Mixing	Mass Loss	Observed	Mixing	Mass Loss	Observed
α Tau	2 $M_\odot$	0.255	0.920	0.315	1.15	570	640	475^{-125}_{+200}	2800	2300	475^{-125}_{+200}	1.39	0.67	6.5[a, b]
β And	2 $M_\odot$	0.205	0.950	0.230	1.25	580	660	425^{-75}_{+150}	1900	1800	425^{-75}_{+150}	1.31	0.69	...
μ Gem	2 $M_\odot$	0.235	0.975	0.245	1.35	580	630	475^{-125}_{+200}	1450	1450	475^{-125}_{+200}	1.40	0.83	...
α Her	5 $M_\odot$	1.063	2.875	1.075	4.00	590	630	550^{-175}_{+225}	1100	1120	550^{-175}_{+225}	1.12	0.83	...
β Peg	5 $M_\odot$	1.150	2.625	1.300	2.93	590	690	425^{-75}_{+150}	7500	4000	425^{-75}_{+150}	1.01	0.41	1.5 ± 0.5[c]
γ Dra	5 $M_\odot$	1.088	2.800	1.105	3.50	590	670	500^{-150}_{+200}	1230	1500	500^{-150}_{+200}	1.11	0.64	1.7[a]

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[a] Lambert and Ries 1981.

[b] This high C/N ratio marks α Tau as an exceptional star in the sample of 32 giants analyzed by Lambert and Ries 1981. The mean C/N ratio for 26 K giant envelopes analyzed by Lambert and Ries is 1.15.

[c] This is a preliminary value from Smith and Lambert 1984.

mixing process. The abundance profiles of both models were recalculated to take account of new information on nuclear reaction rates from Fowler, Caughlan, and Zimmerman (1975) and Harris *et al.* (1983). Initial abundances were assumed to be those of solar system material (Cameron 1973). The abundance profiles were calculated at the end of main-sequence evolution, after a time 7.09×10^8 yr for the 2 $M_\odot$ model and 6.76×10^7 yr for the 5 $M_\odot$ model.

In the case of main-sequence mixing it was assumed that the material in the envelope had been mixed down to a layer $M(r) = M_M$ during main-sequence evolution, being processed at the temperature of this layer over the main-sequence lifetime. The quantity M_M was chosen such that, after a subsequent dredge-up to a depth $M(r) = M_D$ (as determined below) the observed $^{12}C/^{13}C$ ratio would be produced in the envelope. The quantity M_D was determined by requiring that the observed $^{16}O/^{17}O$ ratio (which is virtually unaffected by the mixing) be produced when all layers above M_D were homogenized. In the mass-loss case it was assumed that all layers above $M(r) = M_L$ were lost immediately before the dredge-up; a dredge-up depth $M_D{}'$ was again set by requiring all layers between $M_D{}'$ and M_L to yield the observed $^{16}O/^{17}O$ ratio when mixed, M_L being determined as before by means of the observed $^{12}C/^{13}C$ ratio. In each case $^{16}O/^{18}O$ and $^{12}C/^{14}N$ ratios were then calculated and compared with the observed values (Table 4). The locations of M_D, $M_D{}'$, M_M, and M_L are shown in Figure 3 for the case of α Tau.

The results of the comparison are shown in Table 4. It is evident that the $^{16}O/^{18}O$ ratios from the mixing models are generally consistent with the observations (although only marginally so for β And and β Peg), so long as the "low" rate for $^{18}O(p, \alpha)$ from Harris *et al.* (1983) is employed. The ratios from the mass-loss models are consistently worse, although, except for β And and β Peg, they are still within the estimated uncertainties. The mass-loss explanation is perhaps most likely for α Her, which has the highest $^{16}O/^{18}O$ ratio and in which mass loss is observed to be taking place at present. The mass-loss rates required are greatly in excess of those observed in normal late B and A stars on the main sequence.

It may be noted that for three of these stars Li abundances have been measured (β Peg from Merchant 1967; β And and μ Gem from Luck and Lambert 1982), a fact which severely constrains the possible occurrence of main-sequence mass loss in these stars. Model calculations (discussed by Lambert, Dominy, and Sivertsen 1980) suggest that in stars of these masses, by the end of main-sequence evolution, the original Li has been destroyed by nuclear reactions, except in the outermost 1%–2% of the star by mass, in which the original abundance is maintained. The dredge-up is expected to dilute this remaining Li until the abundance is ~1% of the original (solar system) value, and the measurements referred to above are in qualitative agreement with this. However, if, as in Table 4, the stars must lose 20%–40% of their mass in order to explain the $^{12}C/^{13}C$ ratios, the thin Li-rich layer will be rapidly lost and no Li at all should remain by the time of dredge-up, in contradiction with the observations of these three stars. α Tau, α Boo, γ Dra, and α Ori shows no detectable lithium and may by this criterion have undergone mass loss. However, main-sequence depletion of Li can probably account for the limits on the Li abundance in α Tau, γ Dra, and α Boo (Luck and Lambert 1982). No Li abundance analyses have been reported for α Her and α Sco.

The measured Li abundances do not put serious constraints on the main-sequence mixing models discussed here. We have assumed that the whole of the star from point M_M outward is mixed, which, if strictly true, would lead to the destruction of all the Li in the thin subsurface layer, since the points M_M correspond to temperatures 1.0–1.2 × 10^7 K at which Li is rapidly destroyed. However, if the upper limit of mixing is assumed to be not the stellar surface but a point 2% in mass below it, the Li remains unaffected. The effect of such a modification of the mixing process on the predicted abundances of Table 4 is negligible.

It may be concluded that, except possibly for α Her, main-sequence mixing gives a better explanation of the low $^{12}C/^{13}C$ ratios than does main-sequence mass loss. This conclusion is supported to some extent by the $^{12}C/^{14}N$ ratios (see Table 4).

However, it is apparent that the $^{16}O/^{18}O$ ratios from the mixing models are systematically larger than those observed. Three possible explanations for the difference may briefly be discussed. First, the initial stellar abundances of ^{18}O may have been enhanced over the assumed solar system value, as a result of enrichment of the interstellar medium in ^{18}O in the interval between the Sun's birth and the births of the much younger stars under study. An initial value $^{16}O/^{18}O \approx 400$ would be required, which is less than the ratios seen in the local interstellar medium. Further arguments will be presented in § V showing that it is unlikely that $^{16}O/^{18}O$ has been substantially enhanced during the evolution of the Galaxy. Second, the rate of the $^{18}O(p, \alpha)$ reaction may be even lower than the minimum value from Harris *et al.* (1983). If this is the explanation, then the reduction in the rate would have to be at least a factor 5 below the minimum rate obtained by assuming no contribution from the subthreshold resonance in this reaction (discussed by HL). The minimum reaction cross section corresponds to an extrapolation of that measured by Lorenz-Wirzba *et al.* (1979) at somewhat higher energies; it is unclear, because of the considerable structure in the low-energy cross section which must be averaged over, whether or not Lorenz-Wirzba *et al.*'s extrapolation is reliable, and a discrepancy of a factor 5 cannot be completely excluded (see their Fig. 6). Third, there may be systematic errors in our measurements causing the $^{16}O/^{18}O$ ratios to be overestimated by up to 40%.

c) The $^{16}O/^{17}O$ *Ratios*

The $^{16}O/^{17}O$ ratio is predicted to be a sensitive function of mass for low-mass stars (2–2.5 $M_\odot$ or less; see Fig. 5), as a result of the mass dependence of the depth M_D of dredge-up, on which the surface ^{17}O abundance strongly depends. The range of $^{16}O/^{17}O$ ratios covered by the models of Shadick, Falk, and Mitalas (1980) is similar to the range covered by our measured values, although two stars (β And and α Her) lie slightly outside it. However, our estimates of the masses of the stars in our sample disagree with the masses of the Shadick, Falk, and Mitalas models; if all our stars have masses above 2 $M_\odot$, they should have $^{16}O/^{17}O$ ratios at the low end of the range, around 250, whereas several stars have ratios much higher than this (Fig. 5). It is not clear whether the uncertainty in our mass estimates is sufficient to explain these discrepancies. For all except three members of the sample (β Peg, β And, and α Her), the predicted trend of $^{16}O/^{17}O$ from the models of Dearborn and Gough (1984) agrees approximately with the observations. If the low estimate of the mass of β Peg (~1.75 $M_\odot$) based on the absolute magnitude of Wilson (1976) is adopted, then the $^{16}O/^{17}O$ ratio is β Peg also agrees with the Dearborn and Gough prediction. The $^{16}O/^{17}O$ ratios in α Her and β And are

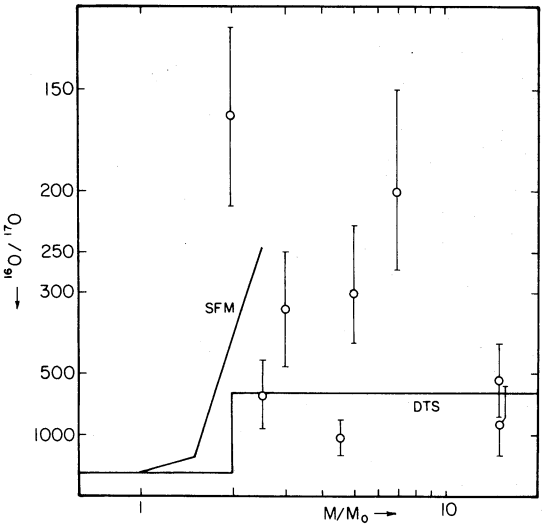

FIG. 5.—The ratio $^{16}O/^{17}O$ as a function of stellar mass for the same stars as in Fig. 4. Full lines represent the ratios predicted by Shadick, Falk, and Mitalas (1980) (labeled SFM) and by Dearborn and Gough (1984) (labeled DG).

much too low to be explained by the Dearborn and Gough models (Fig. 5.)

Some of the sources of uncertainty in the predicted $^{16}O/^{17}O$ ratios may be discussed briefly. However, since the problem with $^{16}O/^{17}O$ ratios is the wide range they cover, rather than their absolute values, we believe that none of them is as relevant to the first dredge-up model as is the uncertainty in the stellar masses. The rate of one of the reactions destroying ^{17}O, $^{17}O(p, \alpha)^{14}N$ is uncertain by up to an order of magnitude at the temperatures in question (Fowler, Caughlan, and Zimmerman 1975). The initial $^{16}O/^{17}O$ ratio in these stars may have been smaller than the solar system value used in stellar evolution models, since the local interstellar medium may be enriched in ^{17}O by 75% (Wannier 1980). Such effects may alter the ordinate levels of the theoretical curves in Figure 5, but this clearly will not improve agreement with the observations.

The wide range in $^{16}O/^{17}O$ ratios is more plausibly explained by assuming that the stars with low ratios have undergone the second dredge-up and are making their second ascent of the giant branch; this implies that their masses are greater than 4.5 $M_\odot$ (Iben and Renzini 1983). The second dredge-up is predicted to bring to the surface material which has undergone shell hydrogen burning to completion. Iben and Truran (1978) present approximate formulae for the amount of this material mixed with the envelope in the dredge-up, and if it is assumed to be the residue of shell hydrogen burning at a characteristic temperature of 5×10^7 K, the amount of ^{17}O mixed into the envelope may be calculated from the CNO-cycle equilibrium abundances at this temperature. The enrichment of the envelope in ^{17}O was found to be negligible if the $^{17}O(p, \alpha)$ reaction rate has the recommended "intermediate" value from Fowler, Caughlan, and Zimmerman (1975). If the minimum possible ("low") rate is used for this reaction, then some enrichment will occur; the envelope mass fraction of ^{17}O increases by $\sim 10^{-5}$ for a 5 $M_\odot$ star, corresponding to a reduction in the Dearborn, Tinsley, and Schramm (1978) predicted $^{16}O/^{17}O$ ratio from 600 to 360. Since ^{14}N is the main product of CNO-cycle equilibrium, there should be an accompanying reduction in the envelope C/N ratio. In view of the uncertainties in the $^{17}O(p, \alpha)$ reaction rate and the stellar evolution models, and of the short times which stars are expected to spend in this phase of evolution, the validity of this explanation for the scatter in $^{16}O/^{17}O$ ratios is unclear.

We may conclude that the variation in $^{16}O/^{17}O$ ratios among the stars studied here is not well understood. There is a need for improved stellar evolution models which will investigate accurately how the depth of the red giant convective envelope varies as a function of mass and how it is affected by other parameters (treatment of convection, mass loss, rotation, and so on).

V. THERMALLY UNSTABLE PULSING SHELL SOURCES IN POPULATION II GIANTS

DBE have postulated that a thermal instability of the hydrogen-burning shell and subsequent dredging (Bolton and Eggleton 1973) may explain the low $^{12}C/^{13}C$ ratios in red giant stars; it appears that this mechanism is most likely to work for objects of lower metallicity. We have attempted to determine whether this process is consistent with the oxygen isotope ratios observed in the mild Population II star Arcturus (α Boo).

The instability of the shell source leads to thermal pulses lasting for $\sim 10^5$ yr, occurring at intervals of $\sim 10^6$ yr. During the period between pulses the convective envelope dredges up some of the material processed during the pulse, thus enriching the surface in CN-cycle products over and above the enrichment due to the first dredge-up. We approximate nucleosynthesis during the pulse by a single zone of temperature 1.82×10^7 K and density 3.39 g cm^{-3}, corresponding to the middle zone (in mass) of the hydrogen-burning shell of Bolton and Eggleton's (1973) 0.8 $M_\odot$ star. This zone is activated for successive intervals of 10^5 yr; after each such pulse a fixed amount of processed material is mixed into the envelope (corresponding to $\sim 2\%$ of the envelope mass per pulse). The initial envelope abundances (Table 5) are taken to be those found by DBE for their 0.75 $M_\odot$ star after the first dredge-up at the end of the main-sequence evolution; ^{13}C and ^{14}N are enhanced at the expense of ^{12}C, ^{16}O and ^{17}O have their original values (since ^{17}O is not expected to be enhanced by the first dredge-up in such low-mass stars), and ^{18}O is slightly depleted from its original value (as is observed in the other stars studied here after their first dredge-up).

It is found that the envelope $^{12}C/^{13}C$ ratios as a function of pulse number agree well with the results of DBE (see their Fig. 1). After ~ 60 pulses the rate of change of $^{12}C/^{13}C$ per pulse becomes very small, and we have taken the results from pulse number 65 to be the final values (as did DBE). This corresponds to a hydrogen shell-burning lifetime of 6.5×10^7 yr, which is a plausible estimate of the duration of the instability. The resulting abundances are shown in Table 5. Agreement

TABLE 5

COMPARISON WITH SHELL-FLASHING MODEL FOR α BOOTIS

Quantity	Initial Value	Final Value	Observed
$^{12}C/^{13}C$	30	8.1	7 ± 1.5
$^{12}C/^{14}N$	3.5	0.44	3.0[a]
$^{16}O/^{17}O$	2630	2000	1100^{-300}_{+400}
$^{16}O/^{18}O$ (low)	500	670	550^{-125}_{+150}
$^{16}O/^{18}O$ (intermediate)	500	1850	550^{-125}_{+150}

[a] Lambert and Ries 1981. See also Kjaergaard *et al.* 1982 (C/N = 2.9), but Mäckle *et al.* 1975 obtain C/N = 0.13.

with observation is poor for the $^{16}O/^{17}O$ ratio, but this is to be expected, since the ^{17}O abundance is extremely sensitive to the pulse temperature, which has been crudely approximated here by a constant value. The $^{16}O/^{18}O$ ratio is reproduced within the error estimates so long as the "low" value for the $^{18}O(p, \alpha)$ reaction rate is used. The $^{12}C/^{14}N$ ratio calculated is much smaller than that observed by Lambert and Ries (1981) and Kjaergaard *et al.* (1982), whereas Mäckle *et al.* (1975) obtained a ratio even lower than our calculated value. Since the Mäckle *et al.* value probably reflects their underestimate of the effective temperature and surface gravity of α Boo, the other two measurements probably rule out the shell-flashing model.

A further point may be noted concerning the $^{16}O/^{18}O$ ratio in Arcturus, arising from the fact that it has a value so close to the solar system ratio. Models of galactic chemical evolution suggest that the secondary elements, produced during stellar evolution from an initial CNO mass fraction Z, should have abundances varying as Z^2; such elements include ^{14}N and ^{18}O (produced from ^{14}N during stellar helium burning). Therefore, since Arcturus is metal-poor relative to the Sun by about a factor 4, its ^{18}O abundance should be 1/16 of the solar value, and its $^{16}O/^{18}O$ ratio should be 1/4 of solar, i.e., ~ 2000. This is clearly not the case, which adds weight to the evidence presented by Edmunds and Pagel (1978) that galactic ^{14}N is mainly of primary origin (see also measurements of N abundances in disk and halo dwarfs by Tomkin and Lambert 1984). It follows that initial stellar $^{16}O/^{18}O$ ratios are never likely to be substantially different from the solar system ratio, as we have assumed throughout. This supposition may be testable from observations of additional metal-poor red giants. It relies on the assumption that, in every stellar generation, a constant fraction of ^{14}N is processed to ^{18}O; since the nucleosynthetic origin of ^{18}O is not well understood, this assumption may not be correct.

VI. CONCLUDING REMARKS

Our results for seven red giants, and those of HL for two red supergiants, show that the $^{16}O/^{18}O$ ratios in these stars are consistent with the solar system and local interstellar values. This result and the absence of an anticorrelation between the $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratios require that (i) the anomalous low $^{12}C/^{13}C$ ratios in some of these stars result from a main-sequence mixing process rather than from mass loss prior to the dredge-up, and (ii) the rate of the reaction $^{18}O(p, \alpha)$ must be very close to, or even less than, the minimum rate quoted by Harris *et al.* (1983). The $^{16}O/^{18}O$ ratio in α Boo indicates that ^{18}O (and therefore presumably its progenitor ^{14}N) are primary rather than secondary nucleosynthesis products. The $^{16}O/^{18}O$ ratio in α Boo is also consistent with the low $^{12}C/^{13}C$ ratio having been produced by hydrogen-burning shell flashes, but the C/N ratio appears to exclude this explanation.

The $^{16}O/^{17}O$ ratios cover a wide range, which may reflect the predicted sensitivity of this ratio to stellar mass; unfortunately, the masses of individual stars are too poorly known to enable this prediction to be tested here. It is equally probable that the range is due to some of the stars in our sample being in a more advanced evolutionary state than we have assumed, or else to variations in the dredge-up depth due to small second-order effects which stellar evolution models have neglected, since the $^{16}O/^{17}O$ ratio is very sensitive to the dredge-up depth.

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