# HOT BOTTOM BURNING IN ASYMPTOTIC GIANT BRANCH STARS AND ITS EFFECT ON OXYGEN ISOTOPIC ABUNDANCES

Arnold I. Boothroyd[1], I.-Juliana Sackmann[2], and G. J. Wasserburg[3]

[1]Canadian Institute for Theoretical Astrophysics, University of Toronto,
60 St. George Street, Toronto, Ontario, Canada M5S 1A7

[2]W. K. Kellogg Radiation Laboratory 106-38,
California Institute of Technology, Pasadena, CA 91125

[3]Lunatic Asylum, Charles Arms Laboratory 170-25,
California Institute of Technology, Pasadena, CA 91125

*Accepted December 1994; appeared in the 20 March 1995 issue:*
*Astrophysical Journal (Letters), 442, L21-L24*

# ABSTRACT

A self-consistent calculation of AGB evolution was carried out, including nucleosynthesis at the base of the convective envelope (hot bottom burning). Hot bottom burning was found to occur for stars between $\sim 4.5$ and $\sim 7\,M_\odot$, producing envelopes with $^{18}\mathrm{O}/^{16}\mathrm{O} \lesssim 10^{-6}$ and $10^{-3} \lesssim {}^{17}\mathrm{O}/^{16}\mathrm{O} \lesssim 10^{-1}$. The $^{17}$O abundance depends sensitively on the nuclear $^{17}$O-destruction rate; this rate is only loosely constrained by the requirement that 1st and 2nd dredge-up models match O-isotope observations of RGB stars (Boothroyd, Sackmann, & Wasserburg 1994). In some cases, high mass loss rates can terminate hot bottom burning before further $^{17}$O enrichment takes place, or even before all $^{18}$O is destroyed. These predictions are in accord with the very limited available stellar observations of J-type carbon stars on the AGB, and with some of the circumstellar $\mathrm{Al_2O_3}$ grains from meteorites. In contrast, data from a number of grains and from most low mass S and C AGB stars ($\lesssim 1.7\,M_\odot$) lie in a region of the $^{18}\mathrm{O}/^{16}\mathrm{O}$ vs. $^{17}\mathrm{O}/^{16}\mathrm{O}$ diagram that is not accessible by 1st and 2nd dredge-up or by hot bottom burning. We conclude that for AGB stars, the standard models of stellar evolution are not in accord with these observations. We surmise that an additional mixing mechanism must exist that transports material from the cool bottom of the stellar convective envelope to a depth at which $^{18}$O is destroyed. This "*cool bottom processing*" mechanism on the AGB is similar to extra mixing mechanisms proposed to explain the excess $^{13}$C (and depleted $^{12}$C) observed in the earlier RGB stage of evolution, and the large $^{7}$Li depletion observed in low mass main sequence stars. Hot bottom burning may lead to significant $^{17}$O enrichment of the interstellar medium; this could be from about 5% to twice the total amount of $^{17}$O produced by supernovae and low mass stars.

*Subject Headings*: dust, extinction — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: AGB and post-AGB — stars: giants

## 1. INTRODUCTION

It has become possible to isolate interstellar oxygen-rich grains from meteorites and to measure their O-isotope ratios with a precision unavailable in typical stellar observations. Each of these grains is considered to be a condensate formed in a stellar outflow, allowing laboratory measurements of isotopic abundance ratios of its parent star. The first three such grains discovered had $^{17}$O enrichment factors between 2 and 7, and relatively minor $^{18}$O depletions, at most a factor of 1.7 (Huss et al. 1992, 1993; Hutcheon et al. 1994; Nittler et al. 1993; Huss et al. 1994). In our previous letter (Boothroyd, Sackmann, & Wasserburg 1994, hereafter BSW-I), we showed that these grains could be accounted for by asymptotic giant branch (AGB) stars that had undergone 1st (and 2nd) dredge-up, where a deep convective envelope reaches down to the ashes of hydrogen burning. This deep mixing can result in major $^{17}$O enrichments of up to a factor of 20 (depending on the stellar mass $M$), but only minor $^{18}$O depletions (a factor of $\lesssim 1.4$). Nittler et al. (1994) recently discovered 21 interstellar oxide grains, some of which show extreme $^{18}$O depletions, up to a factor of 50. It was pointed out by BSW-I that *hot bottom burning* (HBB) in the convective envelopes of relatively massive AGB stars ($\sim 4 - 7\, M_\odot$) could lead to a major destruction of $^{18}$O. In such stars, the surface convective envelope reaches deep enough that the temperature $T_{\rm ce}$ at its bottom is high enough for nuclear burning to take place, resulting in CN-cycle processing of the entire convective envelope. To provide a sound basis for evaluating the effects of HBB, we carried out extensive AGB calculations, following dozens of He shell flashes per star. We present some of the key O-isotope results of these calculations, comparing them to the new grain observations and to recent (less accurate) stellar observations, and discuss the problem of the nuclear reaction rates.

All previous detailed O-isotope calculations had dealt with 1st and 2nd dredge-up only (Dearborn, Tinsley, & Schramm 1978; Landré et al. 1990; Dearborn 1992; Schaller et al. 1992; Bressan et al. 1993; El Eid 1994; BSW-I). The present work is a self-consistent extension of the 1st and 2nd dredge-up work of BSW-I, and represents the first detailed calculations of the effect of HBB on O-isotope ratios.

## 2. METHODS

We considered stars of $M = 3, 4, 4.5, 5, 6$, and $7\, M_\odot$ with solar metallicity ($Z = 0.02$), and 3, 4, 5, and $6\, M_\odot$ with low metallicity ($Z = 0.01$ and 0.001); in higher mass models, we found that core carbon ignition prevented the AGB stage. The models were evolved self-consistently, starting from the pre-main sequence, following the evolution through 1st and 2nd dredge-up, and through dozens of helium shell flashes (thermal pulses) on the AGB, where 3rd dredge-up and HBB can occur; runs were terminated when numerical problems set in. For details, see Boothroyd & Sackmann (1988), Sackmann, Boothroyd, & Fowler (1990), Sackmann & Boothroyd (1992), and Boothroyd, Sackmann, & Ahern (1993). We used a helium mass fraction $Y = 2Z + 0.24$, and $C/Z = 0.2179$, $N/Z = 0.0531$, and $O/Z = 0.4816$ (by mass) as in Keady (1985), similar to Ross & Aller (1976) or Grevesse (1984), and $(^{16}\mathrm{O}/^{17}\mathrm{O})_\odot = 2660$ and $(^{16}\mathrm{O}/^{18}\mathrm{O})_\odot = 500$ (by number). Mass loss was included via a Reimers' (1975) wind $\dot{M} = -\eta(4 \times 10^{-13})LR/M$ (where the star's luminosity $L$, radius $R$, and mass $M$ are in solar units and the mass loss rate $\dot{M}$ is in solar masses per year; $\eta$ is the mass loss parameter). For most runs, we used a modest mass loss rate ($\eta = 1.4$; cf. Kudritzki & Reimers [1978]); as this underestimates the total (observed) AGB mass loss, we also used an intermediate mass loss rate ($\eta = 5$; cf. de Jong [1983]), a high mass loss rate ($\eta = 14$), and tested extreme mass loss rates ($\eta = 50$ and 140).

We used high-temperature opacities from the Los Alamos Opacity Library (LAOL), obtained from Keady (1985). Below $10^4$ K, we generally used molecular opacities from Sharp (1992), but also tested the effect of older molecular opacities from Keady (1985): the effect on HBB nucleosynthesis turned out to be relatively small (see also Boothroyd et al. 1993). Both Sharp and Keady molecular opacities require a value of the convective mixing length parameter $\alpha = 2.1$ in order to match the Sun (Sackmann et al. 1990; Sackmann, Boothroyd, & Kraemer 1993). Nuclear reaction rates from Caughlan & Fowler (1988) were used, except for the $^{17}$O-destruction reactions $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ and $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(e^+\nu)^{18}\mathrm{O}$. For these reactions, we generally used the Landré et al. (1990) rates with parameters $f_1 = 0.2$ and $f_2 = 0.1$. The $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$ rate, which dominates the destruction of $^{18}$O, was taken from Caughlan & Fowler (1988), with the parameter $f = 0$. The rates of these important reactions have not yet been established by nuclear physics laboratory measurements. As a result, the above parameters $f_1$, $f_2$, and $f$ were obtained by BSW-I, by matching 1st and 2nd dredge-up models with observations of O-isotope ratios in stars on the red giant branch (RGB). For $^{18}$O-destruction, $f > 0$ is excluded by the observations. However, for the $^{17}$O-destruction rate, $f_1$ is not tightly constrained, and $f_2$ is not constrained at all (since it affects the rate only above $10^8$ K). In BSW-I, we chose $f_1 = 0.2$ as the best fit, and $f_2 = 0.1$ as an intermediate value; this nuclear parameter set is henceforth referred to as set N1. In this study of more advanced stages of evolution, it was found that the resulting $^{17}\mathrm{O}/^{16}\mathrm{O}$ ratios depended strongly on the choice of $f_1$. Therefore we also explored the consequences of choosing $f_1 = 0.5$ or 1 (referred to as set N2 or N3, respectively); these higher rates give 1st and 2nd dredge-up results that are still consistent with the RGB observations (though not quite as good a fit). We also explored the consequences of using a different functional form from Landré et al. (1990), namely the lower $^{17}$O-destruction rates of Caughlan & Fowler (1988) with their parameter $f_1' = 1$ (referred to as set N0).

## 3. RESULTS

### 3.1. *Hot Bottom Burning (HBB): Stellar Mass, Mass Loss, and Metallicity Effects*

For $Z = 0.02$ with nuclear rate set N1 and modest mass loss ($\eta = 1.4$), the $3\,M_\odot$ star reached a peak value of $T_{\mathrm{ce}} \sim 7 \times 10^6$ K at the 30th flash, too low for HBB. The $4\,M_\odot$ star reached $T_{\mathrm{ce}} \sim 4.5 \times 10^7$ K (still increasing) when the run was terminated (35th flash), high enough for weak HBB, producing $^7$Li but not yet affecting the CNO isotopes. The 4.5 $M_\odot$ and 5 $M_\odot$ stars reached 6 and $7 \times 10^7$ K, respectively (at the 26th and 17th flashes); vigorous HBB produced large amounts of $^7$Li and significant amounts of $^{13}$C, and destroyed most of the $^{18}$O. For 6 and 7 $M_\odot$, $T_{\rm ce}$ levelled off at $\sim 10^8$ K (55 and 70 flashes were followed, respectively). As $^7$Li reached its peak value ($\sim$ 10 times cosmic), $^{18}$O was essentially completely destroyed ($\lesssim 10^{-4}$ solar). Shortly thereafter, $^{13}$C/$^{12}$C reached 0.3 (the nuclear equilibrium value). Subsequently, $^7$Li declined steadily (as its fuel $^3$He was burned), most of the envelope C was burned to N (preventing carbon star formation: see Boothroyd et al. [1993]), and significant additional production of $^{17}$O (a factor of 3 to 5) took place via $^{16}{\rm O}(p,\gamma)$: $^{17}{\rm O}/^{16}{\rm O} \sim (6-9) \times 10^{-3}$ was attained (note $(^{17}{\rm O}/^{16}{\rm O})_\odot = 3.8 \times 10^{-4}$).

With intermediate mass loss ($\eta = 5$), HBB was prevented for 4 $M_\odot$, but was not much affected for $M \gtrsim 5\,M_\odot$. With high mass loss ($\eta = 14$), a peak $T_{\rm ce}$ of only $5 \times 10^7$ K was reached in the 5 $M_\odot$ star, yielding only minor depletion of $^{18}$O. For $M \gtrsim 6\,M_\odot$, high mass loss caused no significant change in HBB. For $\eta = 1.4$, 5, and 14, mass loss rates at the termination of our calculations were $\dot{M} \sim 3 \times 10^{-6}$, $1 \times 10^{-5}$, and $3 \times 10^{-5}$ $M_\odot$/yr, respectively, for all stellar masses ($\sim$ 3 times that at the onset of flashes).

As a general rule, decreasing the metallicity $Z$ mimics the effect of increasing the stellar mass; this also applies to HBB, i.e., $T_{\rm ce}$ is higher for low $Z$. For the 5 and 6 $M_\odot$ cases for $Z = 0.001$, over 60 flashes were followed in each case. For these, results were similar to the 6 and 7 $M_\odot$ $Z = 0.02$ cases, namely, large $^7$Li production, $^{13}{\rm C}/^{12}{\rm C} \approx 0.3$, complete $^{18}$O destruction, and destruction of C (producing N). However, $^{17}$O had been much more strongly enriched by 2nd dredge-up in the $Z = 0.001$ case ($^{17}{\rm O}/^{16}{\rm O} \sim 0.009$; cf. 0.0016 for $Z = 0.02$). HBB first reduced $^{17}$O/$^{16}$O by a factor of 2, because the nuclear equilibrium abundance was lower than the pre-flash abundance. As $T_{\rm ce}$ grows, so does the nuclear equilibrium abundance; at the point where calculations were cut off, $^{17}$O/$^{16}$O reached 0.009 and 0.013 for the 5 and 6 $M_\odot$ cases, respectively. Note that after 60 flashes, $^7$Li had finished its post-peak decline, levelling off at $\log \varepsilon(^7{\rm Li}) \sim -1.5$ (as $^3$He production balanced $^3$He destruction); this is on the lower edge of $^7$Li abundances observed in red giants (Lambert, Dominy, & Sivertsen 1980; Brown et al. 1989). This demonstrates that a low level of $^7$Li does not rule out the presence of HBB. After the drop due to C destruction, C/O slowly grew again, as O burned to N; C/O would reach unity after another few dozen flashes.

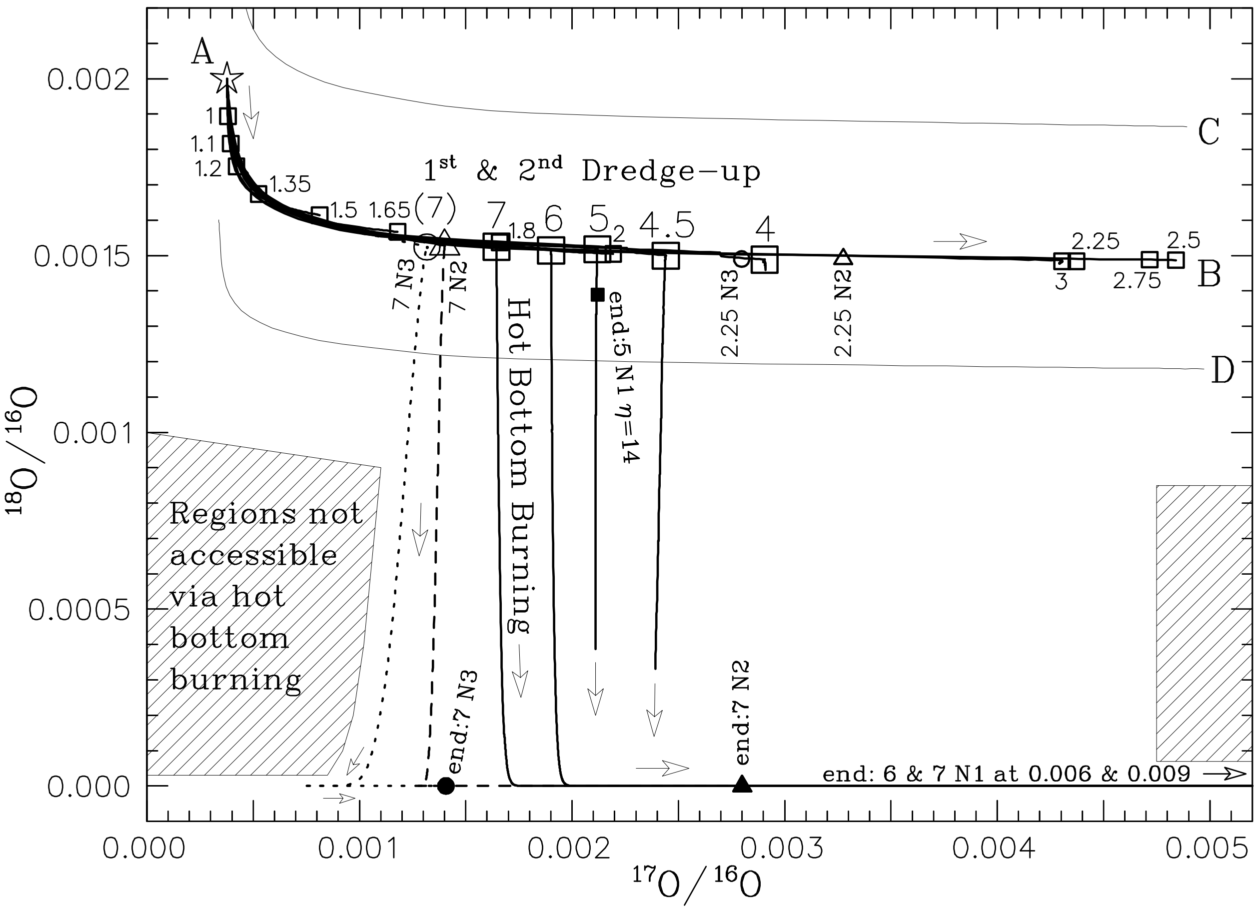

Fig. 1*a*. Predicted evolution of $^{18}O/^{16}O$ vs. $^{17}O/^{16}O$ for 1st and 2nd dredge-up and hot bottom burning (HBB) in $Z = 0.02$ stars of masses from 1 to 7 $M_\odot$. Initial isotope ratios were solar (point A); 1st and 2nd dredge-up move the ratios along the trajectory towards point B. Curves C and D parallel to AB indicate the effect on 1st and 2nd dredge-up of varying initial $^{18}O/^{16}O$ by ±20% from the solar value (and initial $^{17}O/^{16}O$ by ±10%; there is little effect on the final $^{17}O/^{16}O$ ratios attained). Heavy solid curves refer to nuclear rate set N1; termination of 1st dredge-up ($M \leq 3\,M_\odot$) or 2nd dredge-up ($M \geq 4\,M_\odot$) is indicated by small or large open squares, respectively, labelled by the corresponding stellar mass. Dashed and dotted curves refer to the higher $^{17}O$-destruction rates of sets N2 and N3, respectively, with the end of 1st or 2nd dredge-up indicated by open triangles or open circles, respectively (only 2.25 and 7 $M_\odot$ cases are shown). HBB first decreases $^{18}O$ sharply from its 2nd dredge-up value (heavy vertical lines), then increases the $^{17}O$ abundance. Solid squares, triangles, and circles (for sets N1, N2, and N3, respectively) show cases where O-isotope evolution terminates due either to mass loss turning off HBB or to nuclear equilibrium ratios being attained. The hatched regions at lower left and right are inaccessible to either 1st or 2nd dredge-up or HBB, for all initial states considered (cf. curves C and D, and rates N3, N2, N1, and N0).

The predicted O-isotope evolution for a number of stellar masses is shown in Figure 1*a*. The trajectories for 1st and 2nd dredge-up from the results of BSW-I start at point A, moving in the direction of point B. A slight drop in $^{18}\mathrm{O}/^{16}\mathrm{O}$ is followed (for $M > 1.3\,M_\odot$) by a large increase in $^{17}\mathrm{O}/^{16}\mathrm{O}$; termination of dredge-up is indicated by the labelled open squares (note that before this point, very little mass is lost, at low mass loss rates, and thus few grains are formed). For $4.5\,M_\odot \lesssim M \lesssim 7\,M_\odot$ HBB occurs, causing a departure from the curve AB at the point corresponding to 2nd dredge-up. The trajectory falls nearly vertically, with essentially complete destruction of $^{18}\mathrm{O}$; this destruction occurs quite rapidly for $M > 5\,M_\odot$. For $M = 6$ and $7\,M_\odot$ there is subsequently a much slower enhancement of $^{17}\mathrm{O}$, on a timescale that can be comparable to the AGB lifetime; large $^{17}\mathrm{O}/^{16}\mathrm{O}$ values are eventually attained. High mass loss rates ($\eta = 5$ or 14) can terminate or prevent $^{18}\mathrm{O}$ destruction for $M \lesssim 5\,M_\odot$, and reduce slightly the $^{17}\mathrm{O}$ enrichment for $M \gtrsim 6\,M_\odot$ (the endpoint for $5\,M_\odot$ with $\eta = 14$ is shown by the solid square in Fig. 1*a*). Figure 1*a* also shows the results of using higher $^{17}\mathrm{O}$-destruction rates (sets N2 and N3). Note that 1st and 2nd dredge-up follow essentially the same curve from A towards B, but stop at somewhat lower $^{17}\mathrm{O}/^{16}\mathrm{O}$ values. The subsequent evolution with HBB is similar to case N1, except that the $^{17}\mathrm{O}$ enhancement is greatly reduced; for case N3, the maximum value of $^{17}\mathrm{O}/^{16}\mathrm{O}$ hardly exceeds the value at 2nd dredge-up. For $M \gtrsim 6\,M_\odot$, the $^{18}\mathrm{O}$ destruction is rapid enough that $^{18}\mathrm{O}/^{16}\mathrm{O} \approx 0$; mass loss rates extreme enough ($50 < \eta < 140$) to prevent complete $^{18}\mathrm{O}$ destruction in these stars seem improbable, as they would also prevent the stars from reaching the high luminosities ($M_{\mathrm{bol}} \sim -7$) observed in some Magellanic Cloud AGB stars undergoing HBB (Smith & Lambert 1989, 1990). We cannot identify any combination of parameters that would result in low $^{18}\mathrm{O}/^{16}\mathrm{O}$ combined with $^{17}\mathrm{O}/^{16}\mathrm{O} < 0.001$ or $\gtrsim 0.005$: the hatched regions in Figure 1*a* appear to be *inaccessible by HBB*. Stars of near-solar metallicity probably have initial O-isotope ratios within a factor of 2 of solar; such variations do not drastically alter the inaccessible regions.

### 3.2. *Comparison With Grain and Stellar Observations*

The theoretical evolution curves for 1st and 2nd dredge-up and for HBB are combined with the observational data in Figure 1*b*. The stellar observations have large uncertainties (omitted for clarity), but most of the data lie on or below curve AB. Most stellar observations of normal S and C stars (Harris, Lambert, & Smith 1985; Harris et al. 1987; Kahane et al. 1992) lie in the region indicated by the loop; note that their uncertainties (not shown) are of order 50%. These are AGB stars with $\mathrm{C/O} \gtrsim 1$, that have undergone 3rd dredge-up (mixing *s*-process elements and $^{12}\mathrm{C}$ to the surface). Their $^{13}\mathrm{C}/^{12}\mathrm{C}$ ratios are considerably below the nuclear equilibrium value of $\sim 0.3$, indicating that strong HBB cannot be taking place. The O-isotopes of these stars cannot be accounted for by 1st, 2nd, and 3rd dredge-up; nor can they be accounted for by weak HBB, since many have $^{17}\mathrm{O}$ abundances that are too low for such an explanation. These stars are likely to be common low mass AGB stars ($M < 2\,M_\odot$), with $^{17}\mathrm{O}$ abundances resulting from 1st dredge-up, but additional $^{18}\mathrm{O}$ depletion (see § 3.3). The four open circles in Figure 1*b* indicate stellar observations for AGB stars where the presence of strong HBB is suggested by observed values of $^{13}C/^{12}C \sim 0.3$ (Harris et al. 1987). Within the huge uncertainties, these stellar O-isotope ratios are consistent with our models of HBB, but the data are not diagnostic.

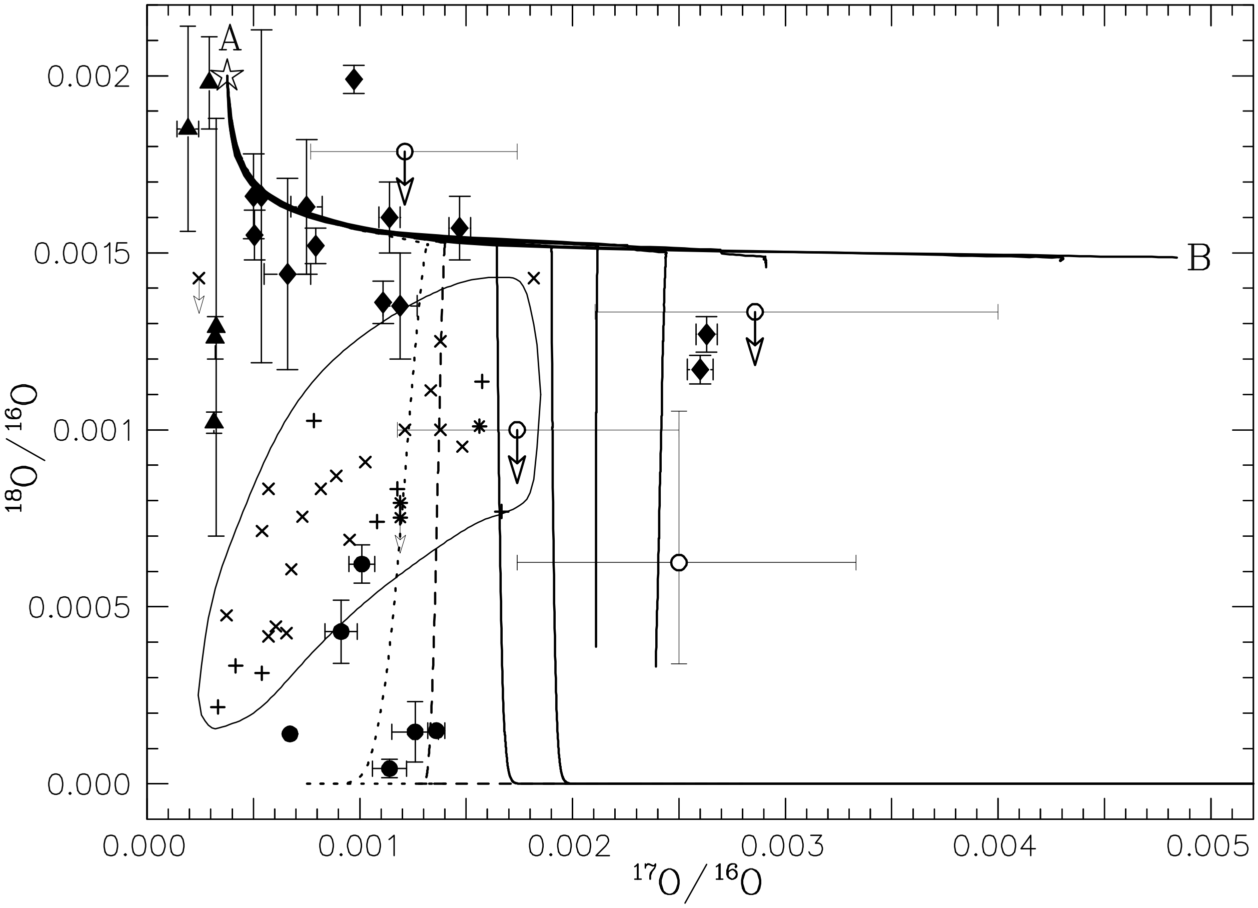

Fig. 1*b*. Comparison of predicted $^{18}O/^{16}O$ and $^{17}O/^{16}O$ (cf. Fig. 1*a*) with grain and stellar observations. Of four J-type carbon stars (○), with $^{13}C/^{12}C \sim 0.3$ indicating HBB, three have only upper limits (heavy arrows) for $^{18}O$. Normal S stars (+) and C stars (×) on the AGB have large errors (not shown), comparable to those of the J-star observations; circumstellar C star observations (✳) of Kahane et al. (1992) are somewhat more accurate. The loop identifies the region where most C and S star observations lie. High precision grain observations are shown by filled symbols, grouped as by Nittler et al. (1994): group 1 (diamonds) are consistent with 1st and 2nd dredge-up, group 2 (●) display very low $^{18}O/^{16}O$ (requiring $^{18}O$ destruction), and group 3 (triangles at left) display low $^{17}O/^{16}O$.

The high-precision grain measurements can be divided into three groups (Nittler et al. 1994). Group 1 grains can be understood in terms of 1st and 2nd dredge-up, with some slight variation of the initial O-isotope ratios (BSW-I). The six group 2 grains stand out, in that they have very low $^{18}O/^{16}O$ ratios, which cannot be the result of 1st and 2nd dredge-up. Three of these grains could possibly be interpreted as products of HBB, provided that they originated from $\sim 7\ M_{\odot}$ stars, and that the $^{17}O$-destruction nuclear rate was very high (set N2 or N3: see Fig. 1*b*). In addition, improbably high mass loss rates

($\eta > 50$) would be required to explain the observed incomplete $^{18}$O destruction (see § 3.1), although it is also possible that some of the $^{18}$O measured in these grains was the result of oxygen contamination during ion probe analysis. On the other hand, the other three group 2 grains lie in the region inaccessible to HBB, near the low mass C and S AGB star observations. Group 3 grains exhibit $^{17}$O/$^{16}$O ratios lower than solar; Nittler et al. (1994) suggest that these might result from $^{16}$O (and $^{18}$O) enriched layers produced in massive stars ($M > 10\,M_{\odot}$). However, the calculations of Weaver & Woosley (1993) suggest that on the average, the opposite is the case in the ejected material ($^{17}$O/$^{16}$O $\gtrsim$ solar). Four of the five group 3 grains might actually originate in low mass stars with initial stellar $^{17}$O/$^{16}$O ratios slightly below solar: one grain lies in the region of group 1, and three lie in a region between groups 1 and 2.

### 3.3. *Cool Bottom Processing*

It is clear that some of the group 2 grains, as well as many of the stellar observations, cannot be explained by HBB, nor by 1st and 2nd dredge-up from the stellar models. The AGB stars in the "inaccessible region" are of low mass ($M < 2\,M_{\odot}$), and their envelopes have undergone CNO cycle processing (as shown by the $^{18}$O depletion). This suggests that some "extra mixing" mechanism exists that transports material from the cool bottom of the convective envelope to sufficient depths that $^{18}$O is destroyed (i.e., $T \gtrsim 2 \times 10^7$ K); we call this "*cool bottom processing*". Such a mechanism has been proposed to explain similar problems with anomalous observations of other isotopes, in earlier stages of evolution. For example, during the RGB phase, shortly subsequent to 1st dredge-up, many low-mass stars have been observed to acquire additional $^{13}$C enrichment, beyond what was produced by 1st dredge-up (see, e.g., Gilroy & Brown 1991). In low-mass, low-$Z$ RGB stars, a pronounced decline in C abundance is observed (cf. Smith & Tout 1992). On the main sequence, $^{7}$Li depletions of more than 2 orders of magnitude are observed in low mass stars. The above abundance anomalies all point to extra nuclear processing of envelope material, at temperatures higher than reached at the bottom of the convective envelopes. It has been frequently pointed out that some slow or episodic extra mixing mechanism must exist, that transports material from the cool convective envelope down to regions hot enough for nuclear processing. Other observations indicate that this mixing cannot be ordinary convection: e.g., helioseismological measurements of the depth of solar convection, and observations of the presence of lithium in $^{13}$C-enhanced RGB stars (Wallerstein & Morell 1994). It is clear that the extent and effect of this extra mixing depends on the stage of evolution, as well as on the star's mass. Effects attributed to such extra mixing have been observed only in relatively low mass stars ($M \lesssim 2\,M_{\odot}$), and the effects seem to be largest for the lowest masses. Although the anomalous $^{18}$O depletion is observed to have occurred in AGB stars, no such depletion has yet been observed in RGB stars; however, more $^{18}$O observations are needed on the RGB, especially in $^{13}$C-enriched stars.

### 3.4. *Enrichment of the Interstellar Medium*

The $^{17}$O enrichment of the interstellar medium has three sources. Supernovae are a key source (Weaver & Woosley 1993); comparable amounts can be produced in low mass stars ($M \lesssim 4\,M_\odot$: BSW-I). For $5 \lesssim M \lesssim 7\,M_\odot$, HBB may produce significant amounts of $^{17}$O, but the amount is much more sensitive to the $^{17}$O-destruction rate than in the other two sources. Thus HBB may be responsible for anywhere between 5% (set N3) and twice as much (set N0) $^{17}$O production as the other two sources combined. HBB stars process too little of the interstellar medium to significantly reduce its $^{18}$O abundance.

We thank Steven E. Koonin for the support supplied by the Kellogg Radiation Laboratory. One of us (A. I. B.) wishes to thank Scott D. Tremaine and Peter G. Martin for the support provided by the Canadian Institute for Theoretical Astrophysics. One of us (I.-J. S.) wishes to thank Robert F. Christy for challenging discussions and gentlemanly help during the many tasks of daily life. This work was supported in part by a grant from the National Science Foundation PHY-8817296, a grant from the Natural Sciences and Engineering Research Council of Canada, NASA grants NAGW-3040, NAGW-3337, and NAGW-3297, and a Caltech Division Contribution 5464(858).

## REFERENCES

Boothroyd, A. I., & Sackmann, I.-J. 1988, ApJ, 328, 653
Boothroyd, A. I., Sackmann, I.-J., & Ahern, S. C. 1993, ApJ, 416, 762
Boothroyd, A. I., Sackmann, I.-J., & Wasserburg, G. J. 1994, ApJ, 430, L77 (BSW-I)
Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C. 1993, A&AS, 100, 647
Brown, J. A., Sneden, C., Lambert, D. L., & Dutchover, E., Jr. 1989, ApJS, 71, 293
Caughlan, G. R., & Fowler, W. A. 1988, Atomic Data Nucl. Data Tables, 40, 205
Dearborn, D. S. P. 1992, Phys. Reports, 210, 367
Dearborn, D., Tinsley, B. M., & Schramm, D. N. 1978, ApJ, 223, 557
de Jong, T. 1983, ApJ, 274, 252
El Eid, M. F. 1994, A&A, 285, 915
Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
Grevesse, N. 1984, Phys. Scripta, T8, 49
Harris, M. J., Lambert, D. L., Hinkle, K. H., Gustafsson, B., & Eriksson, K. 1987, ApJ, 316, 294
Harris, M. J., Lambert, D. L., & Smith, V. V. 1985, ApJ, 299, 375
Huss, G. R., Fahey, A. J., Gallino, R., & Wasserburg, G. J., 1994, ApJ, 430, L81
Huss, G. R., Hutcheon, I. D., Fahey, A. J., & Wasserburg, G. J. 1993, Meteoritics, 28, 369

Huss, G. R., Hutcheon, I. D., Wasserburg, G. J., & Stone, J. 1992, Lunar Planet. Sci., 23, 563

Hutcheon, I. D., Huss, G. R., Fahey, A. J., & Wasserburg, G. J., 1994, ApJ, 425, L97

Kahane, C, Cernicharo, J., Gómez-González, J., & Guélin, M. 1992, A&A, 256, 235

Keady, J. 1985, private communication (LAOL and molecular opacities)

Kudritzki, R. P., & Reimers, D. 1978, A&A, 70, 227

Lambert, D. L., Dominy, J. F., & Sivertsen, S. 1980, ApJ, 235, 114

Landré, V., Prantzos, N., Aguer, P., Bogaert, G., Lefebvre, A., & Thibaud, J. P. 1990, A&A, 240, 85

Nittler, L. R., Alexander, C. M. O'D., Gao, X., Walker, R. M., & Zinner, E. K. 1994, Nature, 370, 443

Nittler, L. R., Walker, R. M., Zinner, E., Hoppe, P., & Lewis, R. S. 1993, Lunar Planet. Sci., 24, 1087

Reimers, D. 1975, in *Problems in Stellar Atmospheres and Envelopes*, ed. B. Bascheck, W. H. Kegel, & G. Traving (New York: Springer), 229

Ross, J. E., & Aller, L. H. 1976, Science, 191, 1223

Sackmann, I.-J., & Boothroyd, A. I. 1992, ApJ, 392, L71

Sackmann, I.-J., Boothroyd, A. I., & Fowler, W. A. 1990, ApJ, 360, 727

Sackmann, I.-J., Boothroyd, A. I., & Kraemer, K. E. 1993, ApJ, 418, 457

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Sharp, C. M. 1992, A&AS, 94, 1

Smith, G. H., & Tout, C. A. 1992, MNRAS, 256, 449

Smith, V. V., & Lambert, D. L. 1989, ApJ, 345, L75

——. 1990, ApJ, 361, L69

Wallerstein, G., & Morell, O. 1994, A&A, 281, L37

Weaver, T. A, & Woosley, S. E. 1993, Phys. Rept., 227, 65