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PREDICTIONS OF OXYGEN ISOTOPE RATIOS IN STARS AND OF OXYGEN-RICH INTERSTELLAR GRAINS IN METEORITES

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ABSTRACT

We carried out detailed, self-consistent calculations for stars from 1 to 9 $M_\odot$ over a wide range of metallicities, following the evolution and nucleosynthesis from the pre–main sequence to the asymptotic giant branch (AGB), in order to provide a self-consistent grid for evaluating stellar oxygen isotopic variations. These were calculated for first and second dredge-up, and for some masses also for third dredge-up and "hot bottom" convective envelope burning on the AGB. We demonstrate that $^{16}O/^{17}O$ in red giant envelopes is primarily a function of the star's mass, while $^{16}O/^{18}O$ is primarily a function of the initial composition. Uncertainties in the ^{17}O-destruction rate have *no effect* on the $^{16}O/^{17}O$ ratio for stars from 1 to 2.5 $M_\odot$, but *do affect* the ratios for higher masses: the stellar $^{16}O/^{17}O$ observations are consistent with the Landré et al. (1990) rates using $f = 0.2$ for $^{17}O(p, \gamma)^{18}F$ and $^{17}O(p, \alpha)^{14}N$, and with the Caughlan & Fowler (1988) rates using $f \approx 1$. The stellar $^{16}O/^{18}O$ observations require $f \approx 0$ in the Caughlan & Fowler $^{18}O(p, \alpha)^{15}N$ rate.

First dredge-up has the largest effect on the oxygen isotope ratios, decreasing $^{16}O/^{17}O$ significantly from the initial value and increasing $^{16}O/^{18}O$ slightly. *Second* and *third dredge-up* have only minor effects for solar metallicity stars. The absence of very low observed $^{16}O/^{18}O$ ratios is consistent with a major increase in the $^{18}O(\alpha, \gamma)^{22}Ne$ rate over the Caughlan & Fowler (1988) value. *Hot bottom burning* in stars above about 5 $M_\odot$ can cause a huge increase in $^{16}O/^{18}O$ (to $\gtrsim 10^6$), and possibly a significant decrease in $^{16}O/^{17}O$; these are accompanied by a huge increase in ^7Li and a value of $^{12}C/^{13}C \approx 3$.

The oxygen isotope ratios in the Al_2O_3 grains (Orgueil grain B, the Murchison 83-5 grain, and the new Bishunpur B39 grain) can be accounted for *if they originated in stars that did NOT have the same initial* $^{16}O/^{18}O$ *ratio.* Thus one *cannot* assume uniform isotope ratios, even for stars of nearly solar composition. The grains' $^{16}O/^{17}O$ ratios, together with the ^{26}Mg excesses that indicate grain formation in a ^{26}Al-rich environment, indicate that the Orgueil grain B and Murchison 83-5 grain originated in stars of roughly 1.5 $M_\odot$, during third dredge-up on the AGB. The new Bishunpur B39 grain originated in a star of either 2 or of 4–7 $M_\odot$.

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

1. INTRODUCTION

It is only in the last few years that intact interstellar grains that originated from stars have been isolated from meteorites. These meteoritic grains permit direct laboratory study of their physical and chemical nature. The first such grains found were carbon-rich (Lewis et al. 1987; Bernatowicz et al. 1987; Amari, Lewis, & Anders 1990). Oxygen-rich interstellar grains are more difficult to isolate. Nonetheless, three such oxygen-rich (Al_2O_3) grains have recently been discovered, having oxygen isotope ratios totally different from solar system values. The first such grain was Orgueil grain B (Huss et al. 1992, 1993; Hutcheon et al. 1994); it was enriched by more than a factor of 2 in ^{17}O but had an approximately solar $^{16}O/^{18}O$ ratio. The second grain, Murchison 83-5 (Nittler et al. 1993), had a similar ^{17}O enrichment and was also somewhat depleted in ^{18}O. A third grain, Bishunpur B39, has just been discovered (see companion *Letter:* Huss et al. 1994); it has even more extreme ^{17}O enrichment (a factor of ~7) and the largest ^{18}O depletion of the three grains (nearly a factor of 2). This *Letter* presents the results of detailed self-consistent calculations of stellar evolutionary models and their nucleosynthesis, providing the oxygen isotope ratios of stellar surface layers at crucial points in the stars' lifetimes as a function of stellar mass, in order to ascertain the astrophysical site where these grains originated.

2. METHODS

We considered stars of masses from 0.85 to 9 $M_\odot$, with metallicities $Z = 0.025$, 0.02, 0.016, 0.01, 0.0044, 0.001, and 0.0001 (see also Boothroyd & Sackmann 1994); for evolutionary program details, see Boothroyd & Sackmann (1988) and Sackmann, Boothroyd, & Fowler (1990). For all runs, we used a helium mass fraction $Y = 2Z + 0.24$. For $Z = 0.02$, we used $C/Z = 0.2179$, $N/Z = 0.0531$, and $O/Z = 0.4816$ (by mass) as in Keady (1985), and similar to Ross & Aller (1976) and Grevesse (1984); we used solar system values of $^{16}O/^{17}O = 2660$ and $^{16}O/^{18}O = 500$ (by number). For some runs, we modified the oxygen isotopic abundances as indicated by the work of Timmes, Woosley, & Weaver (1993), approximately $O/Fe \propto Z^{-1/2}$, ${}^{16}O/{}^{17}O \propto Z^{-1/2}$, and ${}^{16}O/{}^{18}O \propto Z^{-1}$ for Z not too far from solar.

To test the robustness of our results, we explored the effect of uncertainties in nuclear reaction rates. Rates from Caughlan & Fowler (1988) were used for all reactions except ${}^{17}O(p, \alpha){}^{14}N$ and ${}^{17}O(p, \gamma){}^{18}F$, where the Landré et al. (1990) rates were used. For these ${}^{17}O$ rates, there is a large uncertainty in some terms, characterized by a parameter f (where $0 \leq f \leq 1$); we used $f = 0.2$, as recommended by Landré et al. We also tested the Caughlan & Fowler ${}^{17}O$ rates, which have a different functional expression; for these we tried $f = 1$, as recommended by Dearborn (1992), and $f = 0.1$. The ${}^{18}O(p, \alpha){}^{15}N$ reaction has a similar parameter f (Harris et al. 1983); however, Caughlan & Fowler (1988) recommend setting $f = 0$. We generally used $f = 0$ in this reaction, but also tested $f = 0.1$ and $f = 1$.

A mixing length to pressure scale height ratio of $\alpha \equiv l/H_p = 2.1$ was used, consistent with the Los Alamos molecular opacities obtained from Keady (1985), modified below 5000 K to match the low-temperature molecular opacities of Sharp (1992) (see Boothroyd & Sackmann 1992). Some runs were performed to confirm that using the unmodified Keady (1985) opacities, or omitting the red giant wind mass loss, made no difference to first and second dredge-up.

3. RESULTS

Hydrogen burning destroys ${}^{18}O$ at relatively low temperatures via the ${}^{18}O(p, \alpha){}^{15}N$ reaction; from our models, we find that this takes place at 11–18 $\times$ 10^6 K, for stars from 1 to 9 $M_\odot$, respectively. Production of ${}^{18}O$ via ${}^{17}O(p, \gamma){}^{18}F(e^+ \nu){}^{18}O$ is insignificant relative to this destruction. The result is that the initial ${}^{18}O$ is almost completely destroyed in the inner 30%–45% of the star's mass. The isotope ${}^{17}O$ is both produced, via ${}^{16}O(p, \gamma){}^{17}F(e^+ \nu){}^{17}O$, and destroyed, via ${}^{17}O(p, \gamma){}^{18}F$ and ${}^{17}O(p, \alpha){}^{14}N$. A region of enhanced ${}^{17}O$ is built up, where the temperature is too low for complete hydrogen burning but high enough for partial burning (cf. Dearborn 1992). However, for ${}^{17}O$ this simple picture can be complicated by the star's convective core, as discussed below.

After the end of the (core hydrogen burning) main-sequence phase, the star enters the red giant branch (RGB) phase. Convection then reaches down from the surface into the regions where hydrogen burning had depleted ${}^{18}O$ and where ${}^{17}O$ was enriched; the contents of these regions are mixed throughout the star's envelope (*first dredge-up*). Note that almost all stellar mass loss takes place *after* first dredge-up. After the RGB stage, the star contracts as helium burns in the core. As helium is exhausted in the core, the star expands to become a red giant again, on the asymptotic giant branch (AGB). *Second dredge-up* occurs at this point, in a manner similar to first dredge-up. The signature of first and second dredge-up is a *minor increase* in the ${}^{16}O/{}^{18}O$ ratio and a *significant decrease* in the ${}^{16}O/{}^{17}O$ ratio, relative to the initial isotopic composition.

Figure 1 shows our predicted envelope ${}^{16}O/{}^{17}O$ ratios in stars of solar metallicity. (Other metallicities will be presented in Boothroyd & Sackmann 1994.) One sees that ${}^{16}O/{}^{17}O$ drops steeply with stellar mass until a minimum is reached at about 2.5 $M_\odot$, rising slowly thereafter. The *drop* is due to the increase of temperature with stellar mass combined with a small increase in the depth of first dredge-up with stellar mass, such that depths are reached where slightly higher temperatures have produced more ${}^{17}O$; this drop *is not affected by uncertainties in the destruction rate of* ${}^{17}O$. The *rise* after 2.5 $M_\odot$ is due partly to a decrease in the depth of dredge-up and partly to the fact that the main-sequence convective core has become large enough that ashes of core burning are dredged up: in the core, the temperature is high enough that ${}^{17}O$ is both produced *and destroyed*, and therefore the rise *is affected* by the uncertainties in the destruction rate of ${}^{17}O$. Figure 1 shows that effects of second dredge-up are relatively minor (note that this is no longer the case for lower metallicities: see Boothroyd & Sackmann 1994). Our predictions are compared with observations of the ${}^{16}O/{}^{17}O$ ratio in red giant stars (Harris & Lambert 1984a, b; Tsuji 1985; Harris, Lambert, & Smith 1988); note that, in addition to the large uncertainties in the isotope ratios observed in these stars, there is also considerable uncertainty in the estimates of the stars' masses, perhaps a factor of 2. Within these uncertainties, the observations agree reasonably well with the predicted values computed either with the Landré et al. (1990) $f = 0.2$ rates or the Caughlan & Fowler (1988) $f = 1$ rates, but the observations for 15 $M_\odot$ stars rule out the Caughlan & Fowler $f = 0.1$ rates; this is consistent with Dearborn (1992), who ruled out $f = 0$.

Figure 2 shows the effect on ${}^{18}O$ of first and second dredge-up. *The* ${}^{18}O$ *abundance is not altered much from its initial value and thus is not a strong function of stellar mass* (in contrast to the behavior of ${}^{17}O$). One can see that only the lowest ${}^{18}O$-destruction rate, obtained by setting $f = 0$ in the Caughlan & Fowler (1988) rate, produces results consistent with the observations (as noted already by Harris & Lambert 1984a and Dearborn 1992).

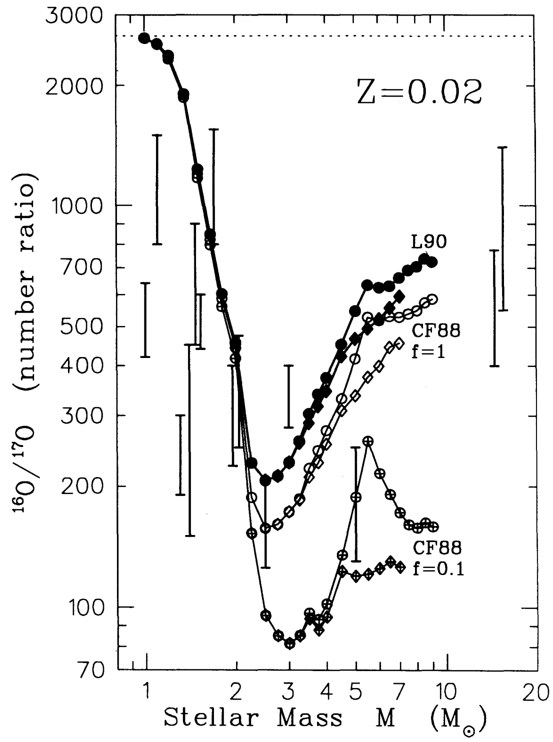

FIG. 1.—The ${}^{16}O/{}^{17}O$ ratio resulting from first dredge-up (*circles*) and from second dredge-up (*diamonds*), for solar composition (Z = 0.02). Calculations were made for different ${}^{17}O(p, \gamma){}^{18}F$ and ${}^{17}O(p, \alpha){}^{14}N$ reaction rates: the Landré et al. (1990) rates (L90: *solid points*), and the Caughlan & Fowler (1988) rates (CF88) with $f = 1$ and 0.1 (*open and crossed points*, respectively). Dotted line indicates the initial (solar) ${}^{16}O/{}^{17}O$ ratio. Stellar observations are shown by vertical error bars.

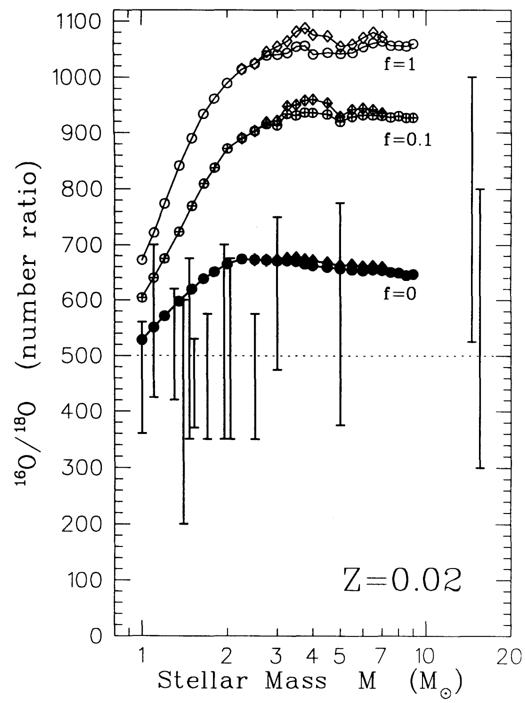

FIG. 2.—The $^{16}O/^{18}O$ ratio resulting from first dredge-up (*circles*) and from second dredge-up (*diamonds*), for solar composition ($Z = 0.01$). Solid, crossed, and open points show results using the Caughlan & Fowler (1988) $^{18}O(p, \alpha)^{15}N$ rate with $f = 0$, 0.1, and 1, respectively. Observations are as in Fig. 1.

Figure 3 compares our calculated oxygen isotope ratios with the high-precision data from the meteoritic Al_2O_3 grains. With the standard ^{18}O-destruction rate ($f = 0$) of Caughlan & Fowler (1988), one obtains a curve of $^{16}O/^{17}O$ versus $^{16}O/^{18}O$ that is too steep to pass through more than one of the grains. If one increases f to values incompatible with the stellar observations (i.e., to 0.1 or to 1), the curve becomes less steep but still cannot pass through more than two of the grains, no matter what initial isotope ratios are chosen. For a given nuclear rate (i.e., a given f value), the position of the curve in Figure 3 is determined primarily by the choice of the initial $^{16}O/^{18}O$ ratio; the initial $^{16}O/^{17}O$ ratio and uncertainties in ^{17}O-destruction rates have relatively little effect.

For our preferred nuclear rates, Figure 4 demonstrates that choosing an appropriate initial $^{16}O/^{18}O$ ratio results in a curve that passes through (or close to) the three distinct data points representing the three separate grains. We varied the oxygen isotopic abundances according to the galactic evolution calculations of Timmes et al. (1993) (see § 2), computing stars of three different near-solar metallicities, namely, $Z = 0.025$, 0.02, and 0.016. *Note that even an order of magnitude change in the value of Z alone, without making a shift in the initial oxygen isotope ratios, has only a very minor effect on the position of the predicted curves and therefore cannot account for the grains* (Boothroyd & Sackmann 1994). The Orgueil grain B can be accounted for by originating in a star having initial $^{16}O/^{18}O \approx 400$ ($Z \sim 0.025$: $^{16}O/^{17}O \sim 2360$), with a mass of $\sim 1.5\ M_\odot$. The grain Murchison 83-5 needs a star with initial $^{16}O/^{18}O \approx 526$ ($Z \sim 0.019$: $^{16}O/^{17}O \sim 2730$) and a mass of $\sim 1.5\ M_\odot$. The new Bishunpur B39 grain can be accounted for by a star with initial $^{16}O/^{18}O \approx 625$ ($Z \sim 0.016$: $^{16}O/^{17}O \sim 2950$); the mass might be $\sim 2\ M_\odot$ or 4–7 $M_\odot$. For all three grains, the oxygen isotope ratios are essentially the result of first dredge-up. *All three grains can be accounted for by starting from stars of similar but not identical compositions*; the $^{16}O/^{17}O$ ratio determines the star's mass and the $^{16}O/^{18}O$ ratio determines the initial stellar $^{16}O/^{18}O$ ratio.

Note that the above Z values should be taken with a grain of salt, as initial stellar $^{16}O/^{18}O$ ratios probably vary more slowly than Z^{-1}: observations of interstellar oxygen isotope ratios (Penzias 1981) suggest that ^{18}O varies precisely in concert with ^{17}O, and the observed $^{16}O/^{18}O$ ratio for Arcturus (α Boo)

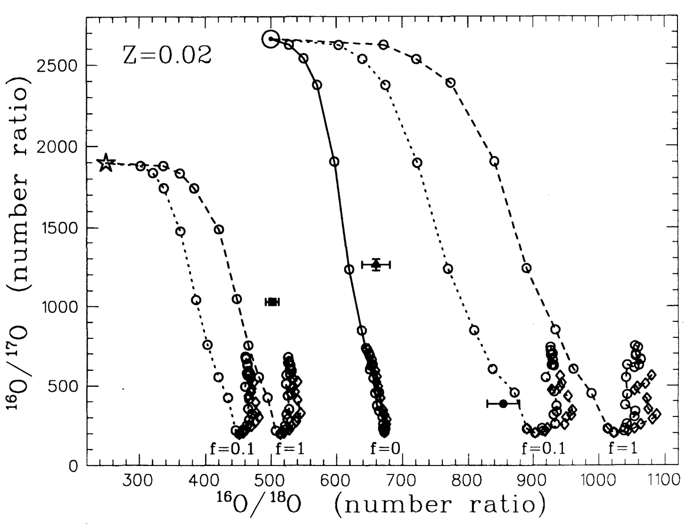

FIG. 3.—Oxygen isotope ratios resulting from first dredge-up (*open circles*) and second dredeg-up (*open diamonds*) in stars (for a range of stellar masses), showing effects of changing the parameter f in the Caughlan & Fowler (1988) $^{18}O(p, \alpha)^{15}N$ nuclear rate ($f = 0$: *solid line*, $f = 0.1$: *dotted*, $f = 1$: *dashed*), and of shifting the initial stellar oxygen isotope ratios (solar: *large dotted circle*; shifted: *large star*). Solid points with error bars show the observed oxygen isotope ratios of the three oxygen-rich grains: Bishunpur B39 (*circle*), Murchison 85-3 (*triangle*), and Orgueil grain B (*square*). Note that no single choice of reaction rate plus initial composition can account for all three grains.

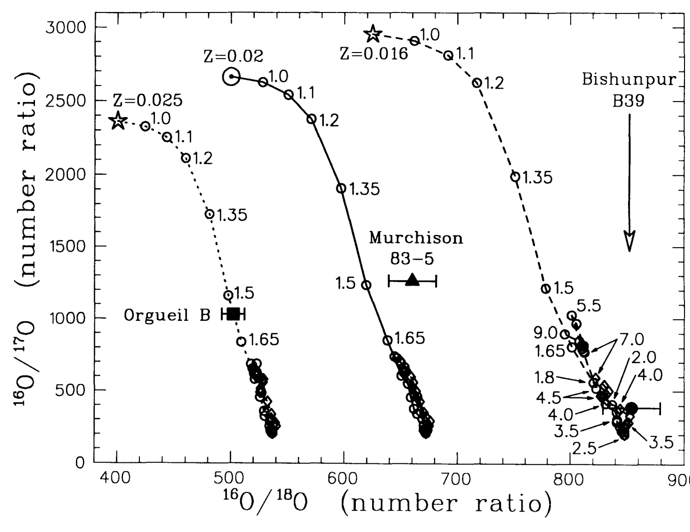

FIG. 4.—Oxygen isotope ratios resulting from first dredge-up (*open circles*) and second dredge-up (*open diamonds*); each point represents a star of a given mass (some masses, in $M_\odot$, are indicated by the numbers next to the curves). The solar metallicity stars ($Z = 0.02$: *solid curve*) initially had solar oxygen ratios (*large dotted circle*); for $Z = 0.025$ (*dotted curve*) and $Z = 0.016$ (*dashed curve*), the initial oxygen ratios (*large stars*) were shifted as explained in the text. Data for the three oxygen-rich grains are indicated by the points with error bars.

of 425–700 (Harris & Lambert 1985b) is lower than the value of $\gtrsim 1500$ implied by $Z \sim Z_{\odot}/3$ (Faber et al. 1985) for $^{16}O/^{18}O \propto Z^{-1}$. Possible alternate depletion mechanisms for stellar ^{18}O that might produce the Bishunpur B39 $^{16}O/^{18}O$ ratio from an initially solar composition include case B mass transfer from a binary companion or rotation-induced extra main-sequence mixing. The latter is less likely: observations suggest that such extra mixing may affect $^{12}C/^{13}C$ ratios observed in stars of mass $\lesssim 2\ M_{\odot}$ (Gilroy 1989) but not $^{16}O/^{18}O$ ratios (Harris & Lambert 1984a, b).

Later, on the AGB, helium shell flashes occur, resulting in a periodic dredge-up of material from below a temporarily extinguished hydrogen burning shell (*third dredge-up*). The material dredged up from this "carbon pocket" is about 25% ^{12}C and 2% ^{16}O by mass (the rest being mainly ^4He); a small amount of mass is dredged up on each flash, increasing the envelope carbon abundance. The oxygen-rich grains can be formed only if $C/O < 1$; this condition can be used to limit the total amount of matter dredged up. One finds that for a solar metallicity star, third dredge-up can increase the envelope ^{16}O abundance by no more than about 2%; similarly, ^{17}O can be decreased by no more than 2%. (Note that even for $C/O > 1$, i.e., a carbon star, third dredge-up still cannot have much effect on the $^{16}O/^{17}O$ ratio unless $C/O \gg 1$, a case which is not observed in AGB stars.)

A similar argument could be made for $^{16}O/^{18}O$ and would result in an identical constraint. However, in the carbon pocket, ^{18}O is created via $^{14}N(\alpha, \gamma)^{18}F(e^+\nu)^{18}O$ and destroyed via $^{18}O(\alpha, \gamma)^{22}Ne$. The computations of Boothroyd & Sackmann (1988) found large amounts of ^{18}O in the carbon pocket for early helium shell flashes, the amount decreasing sharply in later flashes. If dredged up during early flashes, such a large amount of ^{18}O would cause a large enrichment of ^{18}O in the envelope. However, there is evidence (Wiescher et al. 1993) that the $^{18}O(\alpha, \gamma)^{22}Ne$ rate may be larger than the Caughlan & Fowler (1988) rate by a factor of order 100, which would destroy the ^{18}O and prevent such an envelope enrichment. This view is supported by the fact that large ^{18}O abundances are not seen in AGB stars: if anything, ^{18}O is observed to be depleted (Harris et al. 1987).

For AGB stars of $\gtrsim 5\ M_{\odot}$, temperatures at the base of the star's convective envelope can become high enough for nuclear burning to occur there ("*hot bottom burning*"). We find that hot bottom burning leads to *extreme depletion* of ^{18}O in the envelope, with ratios of $^{16}O/^{18}O \sim 10^6$–10^7 being attained. At nearly the same time, the star should become super-rich in ^7Li (a factor of 10–100 higher than the cosmic abundance), and enriched in ^{13}C, i.e., $^{12}C/^{13}C \approx 3$ (Sackmann & Boothroyd 1992; Boothroyd et al. 1993). The $^{16}O/^{17}O$ ratio remains almost unchanged until some time after the ^{18}O is destroyed, but as the temperature at the base of the convective envelope increases, ^{17}O is created at the expense of ^{16}O, and the $^{16}O/^{17}O$ ratio decreases slowly. The signature of hot bottom burning is a *huge increase* of the $^{16}O/^{18}O$ ratio, with a $^{16}O/^{17}O$ ratio which may be *decreased* even beyond that resulting from first and second dredge-up. Note that stars massive enough to undergo hot bottom burning are rare: most interstellar grains will come from less massive stars. None of the three Al_2O_3 grains show evidence of hot bottom burning; even for Bishunpur B39, it is *extremely* improbable that its higher than solar $^{16}O/^{18}O$ ratio resulted from a tiny amount of hot bottom burning.

Our interpretation of the origin of the three Al_2O_3 grains is that they were produced in matter ejected from stars during the late AGB phase of evolution, where there is high mass loss. This is in conformity with the fact that large excesses of ^{26}Mg are observed in all three grains (see Huss et al. 1994), indicating that the grains were formed in an environment rich in the unstable isotope ^{26}Al, which can be mixed into the envelopes of AGB stars by third dredge-up (Forestini, Paulus, & Arnould 1991; Wasserburg et al. 1994).

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