

THE IMPACT OF THE $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ REACTION ON ASYMPTOTIC GIANT BRANCH NUCLEOSYNTHESIS

AMANDA I. KARAKAS^{1,2,3}

Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Weston Creek ACT 2611, Australia; akarakas@mso.anu.edu.au

HYE YOUNG LEE^{1,4}

Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843; hylee@phy.anl.gov

MARIA LUGARO^{1,5}

Sterrenkundig Instituut, University of Utrecht, Postbus 80000, 3508 TA Utrecht, Netherlands; m.lugaro@phys.uu.nl

AND

J. GÖRRES AND M. WIESCHER

Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame,
IN 46556; jgorres@nd.edu, mwiesche@nd.edu

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ABSTRACT

We present detailed models of low- and intermediate-mass asymptotic giant branch (AGB) stars with and without the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction included in the nuclear network, where the rate for this reaction has been recently experimentally evaluated for the first time. The lower and recommended measured rates for this reaction produce negligible changes to the stellar yields, whereas the upper limit of the rate affects the production of ^{19}F and ^{21}Ne . The stellar yields increase by $\sim 50\%$ to up to a factor of 4.5 for ^{19}F , and by factors of ~ 2 to 9.6 for ^{21}Ne . While the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction competes with ^{18}O production, the extra protons released are captured by ^{18}O to facilitate the $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ chain. The higher abundances of ^{19}F obtained using the upper limit of the rate helps to match the $[\text{F}/\text{O}]$ ratios observed in AGB stars, but only for large C/O ratios. Extramixing processes are proposed to help to solve this problem. Some evidence that the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ rate might be closer to its upper limit is provided by the fact that the higher calculated $^{21}\text{Ne}/^{22}\text{Ne}$ ratios in the He intershell provide an explanation for the Ne isotopic composition of silicon-carbide grains from AGB stars. This needs to be confirmed by future experiments of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate. The availability of accurate fluorine yields from AGB stars will be fundamental for interpreting observations of this element in carbon-enhanced metal-poor stars.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB — stars: carbon — stars: Population II

1. INTRODUCTION

Interest in the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction (Q value = 1.741 MeV) came from early pre-supernova models that suggested that the reaction might be important in the helium and carbon burning regions during the supernova (SN). After the shock wave increases the internal temperature and density, the timescale for destruction of ^{18}F via the (α, p) reaction is comparable to that of its β^+ -decay lifetime (Arnett & Truran 1969; Truran et al. 1978; Giesen 1987), where the laboratory half-life of ^{18}F is $\tau_{1/2} = 109$ minutes. The early work by Arnett & Truran (1969) used unpublished theoretical estimates from Fowler; these rates did not appear in Fowler et al. (1975), Harris et al. (1983), or Caughlan & Fowler (1988) and are only valid for $T \geq 800 \times 10^6$ K. Until 2006 the only rate for the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction was the theoretical estimate available in the Brussels nuclear reaction-rate library (Aikawa et al. 2005). The first experiment

aimed at determining the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ rate over a large range of stellar temperatures was carried out by H. Y. Lee et al. (2008, in preparation). This experimental evaluation, when considering its associated uncertainties, presented significant differences compared to the theoretical rate, especially at the low temperatures relevant for He-shell burning in AGB stars ($T \approx 300 \times 10^6$ K). In this paper we investigate the effect of such differences on the nucleosynthesis occurring in AGB models of various initial mass and composition.

These are stars of mass less than $\sim 8 M_{\odot}$ located in the high-luminosity and low-temperature region of the Hertzsprung-Russell diagram. They have evolved through core H and He burning, and are now sustained against gravitational collapse by alternate H and He-shell burning (see Herwig 2005 for a recent review). AGB stars are the site of nucleosynthesis and mixing processes that lead to the production of carbon, nitrogen, fluorine, and heavy elements such as barium and lead. The strong stellar winds associated with these stars ensure that the freshly synthesized material is expelled into the interstellar medium, making AGB stars major factories for the production of the elements in the universe (Busso et al. 1999).

The theoretical estimate of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ rate was not present in our previous works (Lugaro et al. 2004; Karakas et al. 2006), although we included the species ^{18}F because of its important role in the reaction chain $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+ \nu)^{18}\text{O}$ leading to the production of ^{18}O in the He shell. In this article we include

¹ First three authors contributed equally to this work.

² Visiting Scholar, Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843.

³ Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.

⁴ Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, IN 46556.

⁵ Centre for Stellar and Planetary Astrophysics, Monash University, Clayton VIC 3800, Australia.

this reaction in the network and study its effects in detail because preliminary results showed an enhanced production of ^{19}F when employing the new upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ rate. This is of interest because AGB models do not synthesize enough ^{19}F to match the $[\text{F}/\text{O}]$ abundances observed in AGB stars (Jorissen et al. 1992; Forestini et al. 1992). This negative result remains even after examining most of the current error bars of the many reactions involved in the complex chain of production of ^{19}F in AGB stars, such as the $^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ and the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reactions (Lugaro et al. 2004). There are still uncertainties in the stellar models that could affect the match to the observations, in particular extramixing processes, as proposed by Lugaro et al. (2004). However, we will not be able to accurately pin down the effects of such uncertain stellar processes while our estimates of the abundance of ^{19}F in AGB stars are still undermined by uncertainties in the reaction rates involved.

The cosmic origin of fluorine is not yet completely understood. Type II SN explosions (Woosley & Weaver 1995) and stellar winds from Wolf-Rayet stars (Meynet & Arnould 2000) both play a significant role in producing this fragile element alongside AGB stars (Renda et al. 2004). Observationally, AGB stars and their progeny (e.g., post-AGB stars, planetary nebulae) are the only confirmed site of fluorine production thus far (Jorissen et al. 1992; Werner et al. 2005; Zhang & Liu 2005; Pandey 2006), with no clear indication for enhanced F abundances resulting from the ν -process in a region shaped by past SNe (Federman et al. 2005). Moreover, the recent observations of a greatly enhanced F abundance ($[\text{F}/\text{Fe}] = 2.90$) in a carbon-enhanced metal-poor (CEMP) halo star polluted via mass transfer from a companion during its AGB phase (Schuler et al. 2007) represents further strong motivation to better understand the details of the fluorine production mechanism in AGB stars.

The $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction could also affect the abundance of ^{21}Ne in the He-shell of AGB stars. There is a long-standing puzzle concerning the isotopic composition of Ne measured in stellar silicon carbide (SiC) grains extracted from meteorites, which formed in the extended envelopes of carbon-rich AGB stars. About 40% of these grains contain ^{22}Ne and/or ^4He of nucleosynthetic origin (Heck et al. 2007). Being a noble gas, Ne is believed to be ionized and implanted in the SiC dust during the very last phases of AGB evolution (Lewis et al. 1994; Verchovsky et al. 2004). Measurements performed on a large number of grains show that the observed Ne composition can be explained by the mixing of He-shell matter into the envelope material of AGB stars (Lewis et al. 1990; Gallino et al. 1990; Lewis et al. 1994; Heck et al. 2007). While the $^{20}\text{Ne}/^{22}\text{Ne}$ ratios are well reproduced in this scenario,⁶ the $^{21}\text{Ne}/^{22}\text{Ne}$ ratios are higher than predicted by AGB models. Lewis et al. (1994) attributed the higher than predicted abundance of ^{21}Ne to spallation reactions where the grains are bombarded by cosmic rays during their residence time in the interstellar medium. These authors hence related the excesses of ^{21}Ne with respect to the values predicted by AGB models to the age of the grains. However, Ott & Begemann (2000) have shown experimentally that the majority of presolar SiC grains would have essentially lost all the ^{21}Ne produced during spallation by recoil. These authors suggest that the observed variations of the $^{21}\text{Ne}/^{22}\text{Ne}$ ratios in SiC grains are more likely due to the effect of nucleosynthesis in the He-burning shell of their parent AGB star, and this is also

indicated by their correlation with nucleosynthesis effects in the Kr isotopic ratios. The identification of such nucleosynthesis effects, however, are to date missing. The $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction could play a role in this puzzle.

For these reasons we aim to explore in detail the effect of the new experimental evaluation of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ rate, briefly described in § 2, on the production of fluorine and ^{21}Ne in detailed AGB models. Our methods and models are presented in § 3, results in § 4 and § 5, and we finish with a discussion and conclusions.

2. THE $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ REACTION RATE

The measurement of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction cross section is made difficult by the short half-life of ^{18}F . Owing to the problems associated with the production of a long-lived ^{18}F target or a high-intensity ^{18}F beam, the first study of this reaction was based on the measurement of the time-reversed $^{21}\text{Ne}(p, \alpha)^{18}\text{F}$ reaction at the Dynamitron Tandem Laboratory Bochum (Giesen 1987). The cross-section measurements at higher proton energies ($E_p > 3$ MeV) were based on the direct spectroscopy of the emitted α particles, while the lower energy range was investigated using the activation method by analyzing the decay of ^{18}F . The results were not published because the low energy data were affected by the strong beam-induced background from the $^{18}\text{O}(p, n)^{18}\text{F}$ reaction. With the development of an intense ^{18}F beam at the Cyclotron Research Center at the Université de Louvain la Neuve, a direct measurement of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction became possible and the reaction cross section was determined at higher energies ($E_\alpha > 1.4$ MeV corresponding to $E_p > 3.1$ MeV; Lee et al. 2006). The beam intensity, however, was not sufficient to extend these first measurements to energies of relevance for stellar He burning. In a complementary experiment therefore, the low energy range ($E_p \leq 2.3$ MeV) of $^{21}\text{Ne}(p, \alpha)^{18}\text{F}$ was re-investigated at the 4 MV Van de Graaff accelerator at the University of Notre Dame using the activation method (Lee 2006; H. Y. Lee et al. 2008, in preparation).

The cross section of the $^{18}\text{O}(p, n)^{18}\text{F}$ background reaction was measured independently over the entire energy range. The corresponding ^{18}F activity was normalized to the abundance of ^{18}O impurities in the target, and subtracted from the $^{21}\text{Ne}(p, \alpha)$ induced ^{18}F activity. Based on these data, a reaction rate for $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ was determined for the stellar temperature range $0.2 \leq T(\text{GK}) \leq 1.0$ of relevance for AGB star nucleosynthesis. The lower limit of the cross-section measurement is mainly determined by the statistical uncertainty of the activation data, while the upper limit is based on the uncertainty associated with the ^{18}O induced background. The resulting cross-section data were analyzed in terms of the R -matrix theory. The analysis, however, was hampered by the lack of detailed information about the specific parameters of the observed resonances. Figure 1 shows the reaction rate as a function of temperature based on these recent measurements. The solid black line indicates the recommended rate while the dashed line and the dotted lines show the upper and lower limits, respectively. These limits of the reaction rate correlate with the experimental uncertainties in the cross-section data, as well as with the uncertainties from nuclear structure information. Shown for comparison is the predicted Hauser-Feshbach rate as the gray dot-dashed line (Aikawa et al. 2005). The present recommended rate is in good agreement with the Hauser-Feshbach prediction in the characteristic temperature range of AGB stars. Details of the

⁶ The extreme enrichment of ^{22}Ne in these materials is historically known as the Ne-E(H) component in meteorites, whose presence was one of the keys leading to the discovery of stellar SiC grains in meteorites (Anders & Zinner 1993).

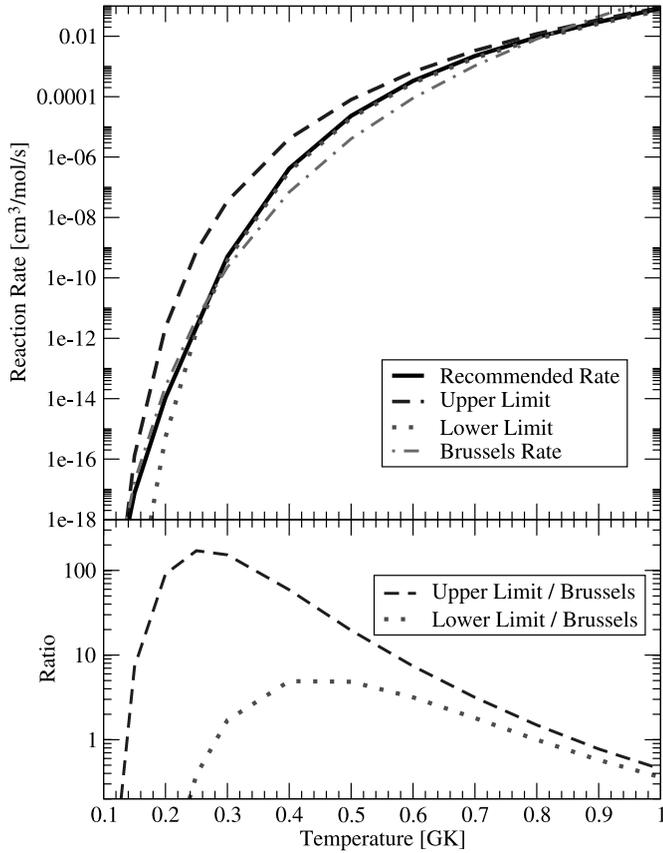


FIG. 1.— Reaction rate of $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ including the upper and lower limits. Also shown is the Brussels theoretical estimate of this rate. In the bottom panel, the ratios of the current upper and lower limits with respect to the Brussels rate are shown.

experiment and the reaction rate analysis will be discussed in a forthcoming paper (H. Y. Lee et al. 2008, in preparation).

3. THE STELLAR MODELS

The numerical method we use has been previously described in detail (Lugaro et al. 2004; Karakas et al. 2006). Here we summarize the main points relevant for this study. We computed the stellar structure first using the Mount Stromlo Stellar Structure code (Lattanzio 1986), and then performed postprocessing on that structure to obtain abundances for 77 species, most of which are not included in the small stellar-structure network. This tech-

nique is valid for studying reactions not directly related to the main energy generation, as they can be assumed to have no impact on the stellar structure. This is certainly the case for studying the effect of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction on AGB nucleosynthesis. On top of including neutron-capture reaction rates from Bao et al. (2000) for nuclei from Ne to S, the main change to the nuclear network for this study is the addition of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate into the 77 species network.

The stellar-structure models used for this study are summarized in Table 1, and have been previously discussed in detail in Karakas & Lattanzio (2007) and references therein. Owing to the fact that we found the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction to affect the abundance of ^{19}F we have concentrated on models that produce the most of it, i.e., $M \sim 3 M_{\odot}$ (Lugaro et al. 2004). We also show results from a lower mass ($1.9 M_{\odot}$) and two intermediate-mass ($5 M_{\odot}$) AGB stars for comparison. Both the $5 M_{\odot}$ models experience proton-capture nucleosynthesis at the base of the convective envelope (hot bottom burning, HBB). The $3 M_{\odot}$, $Z = 0.012$ model was computed with the revised solar abundances from Asplund et al. (2005), whereas the $Z = 0.02$ models were computed with Anders & Grevesse (1989) abundances. The lower metallicity models were computed using Anders & Grevesse (1989) scaled-solar abundances. We also present a model for a $2 M_{\odot}$, $Z = 0.0001$ ($[\text{Fe}/\text{H}] \sim -2.3$) star, which is relevant to the above-mentioned recent observation of highly enhanced fluorine in a halo star of similar metallicity.

A partial mixing zone (PMZ) is required to produce a ^{13}C pocket in the He intershell during the interpulse period. It is in the ^{13}C pocket that neutrons are released by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction (Gallino et al. 1998); in this study we artificially include a PMZ of constant mass at the deepest extent of each third dredge-up (TDU) mixing episode in exactly the same way as described by Lugaro et al. (2004). We include a pocket of $0.002 M_{\odot}$ for all lower mass cases, and we include a pocket of $1 \times 10^{-4} M_{\odot}$ in the $5 M_{\odot}$, $Z = 0.02$ model. Note that these choices result in a ^{13}C pocket between 10% and 15% of the mass of the He-intershell region.

In Table 1 we present the initial mass and metallicity, Z ; the C, N, and O solar abundances used in the structure model where AG89 refers to Anders & Grevesse (1989) and A05 to Asplund et al. (2005); the mass of the partial mixing zone (PMZ); the total number of thermal pulses (TPs) computed; the maximum temperature in the He shell, $T_{\text{He}}^{\text{max}}$; the maximum temperature at the base of the convective envelope, $T_{\text{bce}}^{\text{max}}$; the total mass mixed into the envelope by TDU episodes, $\text{Mass}_{\text{dred}}$; and the final envelope mass M_{env} . All data are in solar units, except the

TABLE 1
DATA AND RESULTS FROM THE STELLAR MODELS

Mass	Z	CNO ^a	PMZ	TPs	$T_{\text{He}}^{\text{max}}$	$T_{\text{bce}}^{\text{max}}$	$\text{Mass}_{\text{dred}}$	M_{env}	C/O	$^{12}\text{C}/^{13}\text{C}$
3.0.....	0.02	AG89	0.002	26	302	6.75	8.1 (−2)	0.676	1.40	118
5.0.....	0.02	AG89	0	24	352	64.5	5.0 (−2)	1.500	0.77	7.84
5.0.....	0.02	AG89	1E−4
3.0.....	0.012	A05	0.002	22	307	7.23	9.2 (−2)	0.806	2.47	168
1.9.....	0.008	AG89	0.002	17	278	3.29	2.2 (−2)	0.222	1.30	138
3.0.....	0.008	AG89	0.002	29	319	10.5	2.1 (−1)	0.549	5.00	519
2.5.....	0.004	AG89	0.002	28	308	7.33	1.9 (−1)	0.685	11.9	1300
5.0.....	0.004	AG89	0	81	377	84.4	2.2 (−1)	1.141	2.64	11.0
2.0.....	0.0001	AG89	0.002	26	307	9.00	2.2 (−1)	0.040	105	2.25 (+4)

NOTE.—See the text in § 3 for details.

^a Initial CNO abundances where AG89 refers to Anders & Grevesse (1989) initial solar or scaled solar abundances, and A05 refers to Asplund et al. (2005) solar abundances.

TABLE 2
STELLAR YIELDS OF ^{19}F AND ^{21}Ne FROM THE AGB MODELS

Mass	Z	CNO	PMZ	$y(^{19}\text{F}_{\text{rec}})$	$f(^{19}\text{F})$	$X(^{19}\text{F})$	$y(^{21}\text{Ne}_{\text{rec}})$	$f(^{21}\text{Ne})$	$X(^{21}\text{Ne})$
3.0.....	0.02	AG89	0.002	5.84 (−6)	0.684	1.526	1.25 (−6)	0.053	4.423
5.0.....	0.02	AG89	0	1.83 (−6)	0.223	1.632	2.09 (−6)	0.050	3.463
5.0.....	0.02	AG89	1E−4	1.87 (−6)	0.227	1.625	2.16 (−6)	0.052	3.327
3.0.....	0.012	A05	0.002	5.66 (−6)	0.676	1.736	1.39 (−6)	0.102	5.330
1.9.....	0.008	AG89	0.002	9.35 (−7)	0.583	1.178	1.60 (−7)	0.032	2.340
3.0.....	0.008	AG89	0.002	1.71 (−5)	1.466	2.407	4.52 (−6)	0.340	9.609
2.5.....	0.004	AG89	0.002	1.33 (−5)	1.752	2.061	2.81 (−6)	0.456	8.364
5.0.....	0.004	AG89	0	1.45 (−7)	0.104	4.582	−2.58 (−6)	−0.627	−1.965
2.0.....	0.0001	AG89	0.002	1.67 (−5)	3.589	1.975	3.23 (−6)	2.080	8.551

temperatures, which are in millions of kelvins. We present some information about the light elements, including the surface C/O and $^{12}\text{C}/^{13}\text{C}$ number ratios at the last computed time step.

4. RESULTS

In Table 2 we show results from the stellar models that employed the recommended rate of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction. For each mass and Z value, we show the C, N, and O abundances used in the structure model (as for Table 1), the mass of the PMZ used in the computation, the yield (y) of ^{19}F , the production factor (f) of ^{19}F , and the multiplication factor (X) needed to obtain the upper limit ^{19}F yield from the recommended-rate yield. All yields are in solar masses, the production factors f and the multiplication factors are dimensionless quantities. The same information is also presented for ^{21}Ne for each model. We compute stellar yields by integrating the surface abundances lost in the wind over the stellar lifetime, normalized to the initial abundance in the wind (see, e.g., Karakas & Lattanzio 2007). The production factors are defined according to $f = \log(X_{\text{end}}/X_{\text{initial}})$, where X_{end} is the mass fraction at the tip of the AGB and X_{initial} is the initial mass fraction. The yields from the recommended calculations are essentially the same as the yields obtained from models that employed the lower limit, adopted the Brussels theoretical rate, or did not include the $^{18}\text{F}(\alpha, p)$ reaction at all.

From inspection of Table 2 we can see that employing the new upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction results in a significant increase in the production of ^{19}F and ^{21}Ne . The change in the yield increases with decreasing metallicity, at a given mass, with the largest change found in the $5 M_{\odot}$, $Z = 0.004$ model where the ^{19}F yield increased by a factor of 4.5. The largest change in the ^{21}Ne yield is a factor of 9.6 for the $3 M_{\odot}$, $Z = 0.008$ model. While we find large increases in the F yield for both the intermediate-mass AGB models, the absolute yields are significantly smaller than those from the lower mass objects; this is because ^{19}F is destroyed by HBB. For example, the $5 M_{\odot}$, $Z = 0.02$ model produced 3 times less ^{19}F than the $3 M_{\odot}$, $Z = 0.02$ case, whereas the $5 M_{\odot}$, $Z = 0.004$ model produced about 40 times less ^{19}F than the $2.5 M_{\odot}$, $Z = 0.004$ model. From Table 2 we note that the PMZ had little effect on the production of ^{19}F and ^{21}Ne in the $5 M_{\odot}$, $Z = 0.02$ model.

While increases in the ^{21}Ne yield as a consequence of using the upper limit of the $^{18}\text{F}(\alpha, p)$ rate are larger than for ^{19}F , the overall amount of this isotope produced by AGB stars remains small. This is reflected in the production factors that are $f \lesssim 0.3$ for all models but the $2.5 M_{\odot}$, $Z = 0.004$ and $2 M_{\odot}$, $Z = 0.0001$ models, where the production factors are 0.45 and 2.08 dex, respectively. The increase at very low metallicity might be significant for chemical evolution studies of the Ne isotopes. Over-

all however, we conclude that the rare isotope ^{21}Ne is not significantly produced in AGB stars, even when using the upper limit of the $^{18}\text{F}(\alpha, p)$ reaction in the calculations. Most of this isotope in the Galaxy originates from Type II SN (Woosley & Weaver 1995; Timmes et al. 1995), although it would still be an interesting exercise to include our AGB yields in a chemical evolution model. The impact of the upper limit on ^{21}Ne production is more important for stellar SiC grains; this is discussed further in § 5.

In this section we did not discuss the surprising result that the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction affects the production of ^{19}F in AGB stars. It is not intuitive why this should be the case, so in the next section we outline the mechanism responsible for the production of the extra fluorine.

4.1. The ^{19}F Production Mechanism

The enhanced abundance of ^{19}F may be explained by considering the $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reaction chain. Including the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction reduces the abundance of ^{18}O because it competes with ^{18}O production via the $^{18}\text{F}(\beta^+ \nu)^{18}\text{O}$ decay. However, the extra amount of protons from (α, p) enhances the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction rate, even though ^{18}O production has been deprived from the decay. In other words, the sum $N_{18\text{O}} + N_p$ (where N_i is the abundance by number of nucleus i) remains constant; however, the product $N_{18\text{O}}N_p$, on which the number of $^{18}\text{O}+p$ reactions depends, is maximized when $N_{18\text{O}}$ is equal to N_p .

We can analytically analyze the effect of the extra protons on the ^{19}F production in the He shell. We simplify the $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reaction chain to the $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reaction. In a He-rich region, all ^{14}N is converted to ^{18}O via the (α, γ) reaction; this either decays to ^{18}O via the β^+ decay with a branching ratio of f or makes extra protons via the (α, p) reaction with a branching ratio of $1 - f$. Then the number density of ^{18}O , $N_{18\text{O}}$, is written as $fN_{14\text{N}}$, and for protons, N_p , as $N_{p_0} + (1 - f)N_{14\text{N}}$, where N_{p_0} is the original number density of protons without the inclusion of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction, and $N_{14\text{N}}$ is the ^{14}N from the H-burning ashes. Then the reaction rate of $^{18}\text{O}(p, \alpha)^{15}\text{N}$ can be written as

$$N_{18\text{O}}N_p \langle \sigma v \rangle_{(p, \alpha)} = fN_{14\text{N}} [N_{p_0} + (1 - f)N_{14\text{N}}] \langle \sigma v \rangle_{(p, \alpha)} \quad (1)$$

$$= fN_{14\text{N}}N_{p_0} \langle \sigma v \rangle_{(p, \alpha)} [1 + (1 - f)N_{14\text{N}}/N_{p_0}]. \quad (2)$$

Since $fN_{14\text{N}}N_{p_0} \langle \sigma v \rangle_{(p, \alpha)}$ is the rate of $^{18}\text{O}(p, \alpha)^{15}\text{N}$ without including the $^{18}\text{F}(\alpha, p)$ reaction, the term $[1 + (1 - f)N_{14\text{N}}/N_{p_0}]$ may be thought of as an ^{19}F enhancement factor. The overall

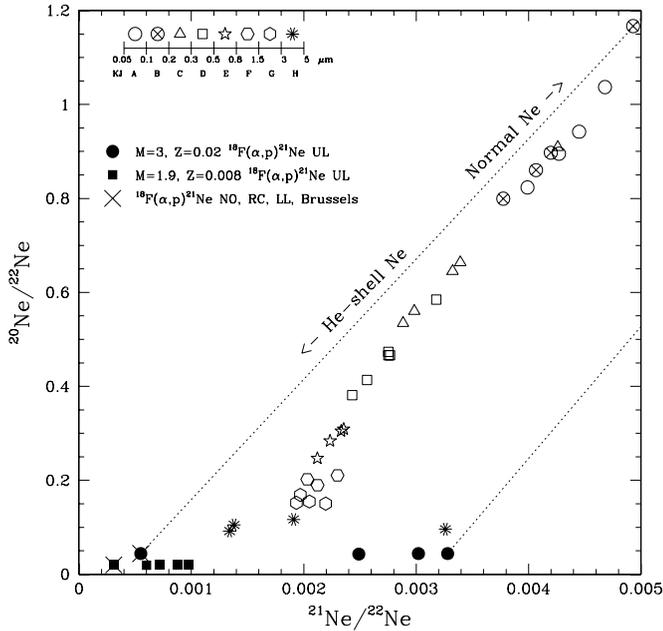


FIG. 2.—Ne isotopic ratios observed in meteoritic SiC grains and predicted in the intershell of our $3 M_{\odot}$, $Z = 0.02$ and $1.9 M_{\odot}$, $Z = 0.008$ models. The plot is similar to Fig. 8 of Lewis et al. (1994), where we have taken their measurements and added the model predictions. For each model we plot the Ne isotopic ratios in the He intershell at the end of each TP occurring when $C/O > 1$ is satisfied in the envelope of the star. The crossed filled symbols represent models computed without the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate, which give a constant result. The filled symbols represent models run using the upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate. Dotted lines connect the normal Ne component of solar composition to the He-shell Ne component corresponding to the final compositions of the intershell for the $3 M_{\odot}$, $Z = 0.02$ model.

^{19}F production increases as long as $N_{14\text{N}}/N_{p_0} > 1$, and this condition is well satisfied in the He-burning shell. During the network calculation a realistic $N_{14\text{N}}/N_{p_0} \approx 10^{10}$; this ratio is large enough to explain the enhanced fluorine production in the stellar models.

As possible sources of uncertainty we can ignore the other $^{18}\text{F} + \alpha$ channels, that is the (α, n) and the (α, γ) . According to the Brussels theoretical estimate (Aikawa et al. 2005) the (α, γ) reaction is approximately 2 orders of magnitude slower at 0.3 GK than the (α, p) , whereas the (α, n) is 40 orders of magnitude slower.

5. ^{21}Ne IN METEORITIC SiC GRAINS

To address the puzzle of the $^{21}\text{Ne}/^{22}\text{Ne}$ ratio in stellar SiC grains we have analyzed the effect of using the new $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate on the ^{21}Ne abundance in the He intershell of AGB stars. The results are shown in Figure 2 and compared to the SiC data from Lewis et al. (1994). The plot is similar to Figure 8 of Lewis et al. (1994), where we have taken their measurements and added our new model predictions. The SiC data are derived from measurements on samples of grains *in bulk*, i.e., collections of a large number (\sim millions) of grains. Different symbols represent measurements done on collections of grains sampling different sizes, from 0.01 to 5 μm , as described in the figure. Note that, since measurements in bulk are performed on millions of grains, they can only be used to derive the average properties of the parent stars of the grains.

Each data point in Figure 2 is interpreted as having been produced by a mixture between the material initially present in the envelope of the star and the material mixed from the He intershell into the envelope by TDU. These two “ingredients” are

referred in the plot as the normal Ne and the He-shell Ne components, respectively. The normal component is taken to have solar composition. The SiC grains show a composition dominated by a He-shell component extremely enhanced in ^{22}Ne with respect to solar, as it is the composition of the He intershell of AGB stars. However, it is clear that the data points do not lie on the straight mixing line between the two components (the dotted lines in the plot), which means that the He-shell component must be variable if we want to account for all the different measurements.

Model predictions presented in the plot are for the $3 M_{\odot}$, $Z = 0.02$ and $1.9 M_{\odot}$, $Z = 0.008$ models. These models are the best within our sample, out of those that are listed in Table 1, to represent the parent stars of SiC grains. This is because they reach carbon-rich conditions toward the end of their evolution (a necessary condition for the formation of SiC) and have masses (between 1.5 and $3 M_{\odot}$), and metallicities (close to solar) in the range of the best candidate SiC parent star models (see e.g., Lugaro et al. 1999, 2003 for a thorough discussion).

When we compute our models using the recommended, lower limit, or Brussels theoretical evaluation of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate, the results are equivalent to the models computed without the inclusion of this reaction, and they are the same as those presented by Gallino et al. (1990). The $^{21}\text{Ne}/^{22}\text{Ne}$ ratio in the intershell is constant ≈ 0.0004 and the rightward shift to higher $^{21}\text{Ne}/^{22}\text{Ne}$ ratios observed in the grains cannot be reproduced. Note that in this case the abundances of ^{20}Ne and ^{21}Ne are barely modified in the intershell; in particular ^{21}Ne is destroyed by factors 5–50 in the H-burning ashes and restored to its original solar system value by neutron-capture reactions on ^{20}Ne during the TPs, with neutrons released by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction. On the other hand, models computed with the upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate show an increase in the ^{21}Ne abundance, and hence in the $^{21}\text{Ne}/^{22}\text{Ne}$ ratio in the intershell of up to a factor of 6, which is the number needed to reach up to the most extreme data point observed at $^{21}\text{Ne}/^{22}\text{Ne} = 0.0033$. The predicted intershell $^{21}\text{Ne}/^{22}\text{Ne}$ ratio increases with pulse number and with the stellar mass because the temperature increases and the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction becomes more efficient. The last computed TPs reached 302 and 278×10^6 K for the 3 and the $1.9 M_{\odot}$ models, respectively.

Another possible way of producing a higher abundance of ^{21}Ne in the He intershell is by increasing the neutron-capture cross section of ^{20}Ne . The value we use is 0.199 mbarn at 30 keV, which is recommended by Bao et al. (2000) and corresponds to the experimental estimate of Winters & Macklin (1988). A much higher value of 1.5 mbarn at 30 keV was previously suggested by Almeida & Kaeppler (1983), in which case the final $^{21}\text{Ne}/^{22}\text{Ne}$ ratio in the intershell of our $3 M_{\odot}$, $Z = 0.02$ model is equal to 0.002. However, the data of Almeida & Kaeppler (1983) have recently been re-analyzed (M. Heil 2007, private communication) resulting in a much lower cross section of 0.303 mbarn at 30 keV. With this latest evaluation the final $^{21}\text{Ne}/^{22}\text{Ne}$ ratio in the intershell of our $3 M_{\odot}$, $Z = 0.02$ model reaches only 0.00073. We also checked that possible changes in the neutron capture cross section of ^{21}Ne itself, and the current uncertainties of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction rate (Karakas et al. 2006) do not lead to significant variations in the abundance of this isotope. These considerations lead us to conclude that the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate being close to its upper limit would be a promising explanation for the $^{21}\text{Ne}/^{22}\text{Ne}$ ratios in SiC grains.

Finally, we note that increasing $^{21}\text{Ne}/^{22}\text{Ne}$ ratios are correlated with increasing $^{86}\text{Kr}/^{82}\text{Kr}$ ratios measured in SiC grains (see Fig. 5 of Ott & Begemann 2000). This correlation can be qualitatively matched by considering that both the ^{21}Ne and ^{86}Kr abundances

in the intershell increase with increasing temperature. This is because ^{86}Kr is produced via the branching point at ^{85}Kr during the high-neutron density flux produced by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction during TPs (see e.g., Abia et al. 2001). Quantitatively, however, our models can only match the lowest observed $^{86}\text{Kr}/^{82}\text{Kr}$. It remains to be seen if this mismatch can be attributed to uncertainties in the nuclear properties of the ^{85}Kr branching point, or to intershell temperatures higher than those of our models during the late AGB or the post-AGB phases. Further work is needed to address this point.

6. DISCUSSION

In Figure 3 we show the evolution of the surface $[\text{F}/\text{O}]$ ratio as function of the C/O ratio for four AGB models, compared to the observations of fluorine-enhanced stars from Jorissen et al. (1992). The models are selected to best represent the features of the observed stars, that is, stars with masses in the range $1.5\text{--}3 M_{\odot}$ (Wallerstein & Knapp 1998), and with metallicities around $Z = 0.01$. Similarly to the yields, the final surface $[\text{F}/\text{O}]$ ratios from these models are roughly 50% to $\sim 140\%$ higher when calculations are done using the new upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction.

From Figure 3 we see that using the new upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction can result in a match between the stellar models and the stars with the highest observed ^{19}F abundances, but only for the very high C/O ratios of $\sim 4\text{--}5$, found in the $3 M_{\odot}$, $Z = 0.008$ model. In the lower mass models and in the $3 M_{\odot}$ of solar metallicity, the new upper limit does not result in a match between the predicted and observed $[\text{F}/\text{O}]$ abundances. Lugaro et al. (2004) suggested that extramixing processes in AGB stars may help to solve this problem by converting C into N, hence decreasing the C/O ratio for a given ^{19}F abundance. Further indication of this possibility is the fact that for any given C/O ratio MS and S stars with the higher ^{19}F abundance also have N excesses, and lower $^{12}\text{C}/^{13}\text{C}$ ratios than predicted by standard models (Abia & Isern 1997). Detailed studies of the possible effects of extramixing phenomena are required, and will have to analyze the impact of using the higher ^{19}F abundance obtained using the upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate.

There are many uncertainties that affect AGB stellar models including the treatment of convection and mass loss (see Herwig 2005 for a detailed discussion). One modeling uncertainty that might affect the results is that most of the stellar models did not lose all of their convective envelopes when the evolution sequences ended, that is, they did not leave the AGB track, and could, in principle, experience extra TPs and TDU episodes. This possibility is discussed in Karakas et al. (2007) where it was estimated that one more TP may occur for, e.g., the $3 M_{\odot}$, $Z = 0.012$ model. We do not repeat this exercise here owing to the uncertainty of the efficiency of the TDU at small envelope masses (see discussion in Karakas & Lattanzio 2007), but note that more TDU episodes would further enrich the ^{19}F and ^{12}C abundances at the stellar surface.

Another modeling uncertainty that will affect our results is the choice of mass-loss rate during the AGB. We used the Vassiliadis & Wood (1993) mass-loss prescription that was empirically derived from Mira-type variables and might overestimate mass loss for semiregulars, thus terminating the TP-AGB phase too early and hampering the formation of C stars at low masses. At solar metallicity we do not form carbon-rich stars with initial masses below $2.5 M_{\odot}$ (Karakas et al. 2002), whereas typical C-star initial masses are $\sim 2 M_{\odot}$ (Claussen et al. 1987), although this result is somewhat model dependent (Abia et al. 2001; Kahane et al. 2000). Regardless, this observational result

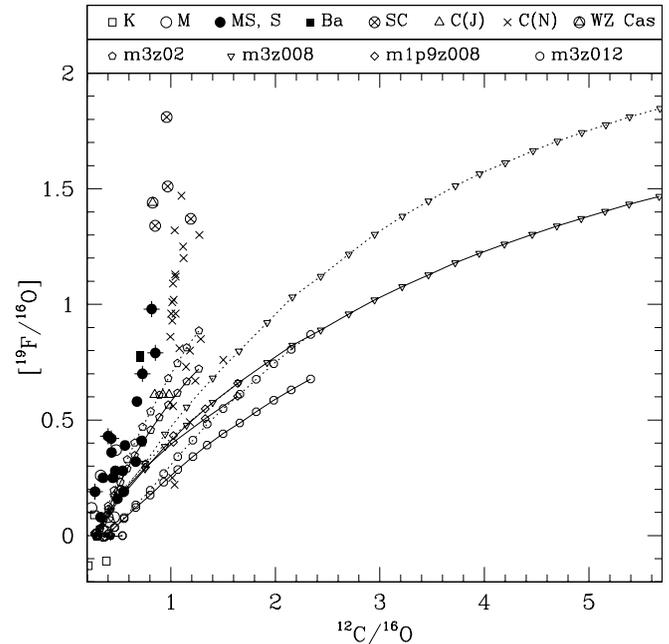


FIG. 3.— Comparison of fluorine abundances observed by Jorissen et al. (1992) and model predictions for selected stellar models: $3 M_{\odot}$ with $Z = 0.02$, 0.012 , and 0.008 ; and $1.9 M_{\odot}$ with $Z = 0.008$. All models include a PMZ of $0.002 M_{\odot}$. Predictions are normalized in such way that the initial ^{19}F abundance corresponds to the average F abundance observed in K and M stars (see Jorissen et al. 1992). Crossed MS and S symbols denote stars with large N excesses. Each symbol on the prediction lines represents a TDU episode. Solid lines: Calculations performed using no $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction, which are equivalent to using the current lower limit, recommended value and Brussels library rate. Dotted lines: Calculations performed using the current upper limit of the rate.

is in contradiction to our models, and is caused partly by our choice of mass loss, and also because we do not find efficient enough (or any) TDU in the low-mass AGB models of $\approx Z_{\odot}$. Certainly, a different choice of mass loss would have a significant effect on the stellar structure and on the resulting F and ^{21}Ne yields. We address this point in Karakas et al. (2006) for intermediate-mass AGB stars where the yields of ^{25}Mg and ^{26}Mg changed by more than an order of magnitude by using the Reimers mass-loss rate on the AGB instead of Vassiliadis & Wood (1993); we speculate that we would expect similar changes to the yields of lower mass stars, but more work is needed to address this important point. One final comment is that the $3 M_{\odot}$, $Z = 0.02$ model becomes a C-rich star at a total (current) mass of $\sim 2.3 M_{\odot}$. Given the uncertainties in deriving total masses of C stars this is not entirely out of the range of expected C-star masses.

In Figure 4 we show the bolometric luminosities plotted against effective temperature for two stellar models that become C-rich near the tip of the TP-AGB phase. Figure 4 can be compared to Figure 6 in Busso et al. (2007) with luminosities and temperatures from a selection of AGB stellar models computed with the FRANEC code (Straniero et al. 2003), plotted against bolometric luminosities derived from observations of C-rich stars (see also Guandalini et al. 2006; Whitelock et al. 2006). In comparison to the FRANEC models, AGB models computed with the Monash stellar structure code cover a similar range of T_{eff} from 3200 to 2500 K as most of the carbon stars, and cover the observed range of bolometric luminosities. Similar to the FRANEC models, we cannot match the T_{eff} values of the coolest stars with temperatures ~ 2000 K. However, we must be cautious about making conclusions from this comparison because we are showing

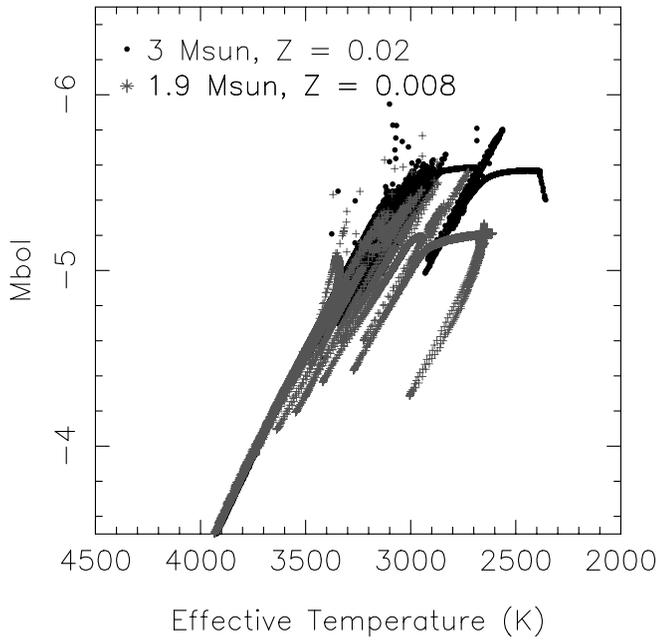


FIG. 4.—Bolometric luminosity, M_{bol} , vs. effective temperature, T_{eff} , for the $3 M_{\odot}$, $Z = 0.02$ (black dots), and the $1.9 M_{\odot}$, $Z = 0.008$ (gray crosses) models during the TP-AGB phase. The large variation in M_{bol} and T_{eff} shown in this diagram is caused by the change in these observables during the AGB life cycle (i.e., thermal pulse–dredge-up–interpulse).

the entire AGB evolutionary sequence, not just the sequences when the model stars have $C/O > 1$ at the surface. Second, we do not include a realistic treatment of low-temperature molecular opacities but instead we approximated the opacity from CN, CO, H₂O, and TiO using the formulations prescribed by Bessell et al. (1989) and corrected by Chiosi et al. (1993). These are fits to the molecular opacities of Alexander (1975) and Alexander et al. (1983) and while they do include a dependence on envelope composition do not treat properly treat C-rich compositions (see, for example, Marigo 2002).

Both Marigo (2002) and Busso et al. (2007) have outlined the importance of using realistic low-temperature molecular opacities in detailed AGB models. Future work will study the effect of carbon-rich molecular opacities on the stellar structure and nucleosynthesis. Marigo (2002) found that the inclusion of C-rich opacities truncated the TP-AGB evolution fairly quickly (that is, in a couple of TPs) once the C/O ratio exceeded unity. This is because the C-rich molecules that form under such conditions caused the star to become larger and cooler, and this in turn increased the mass-loss rate. One of us (A. I. Karakas et al., in preparation) is currently studying the effect of such opacities on detailed AGB models and noticed similar trends, in that the evolution ends before the C/O ratio exceeds values much larger than ~ 2 . One consequence of this is that we would no longer predict the large C/O ratios found in the $3 M_{\odot}$, $Z = 0.008$ model (see Fig. 3) and, subsequently, values of $[F/O]$ greater than $\simeq 1$.

Another exciting future opportunity is represented by the comparison of our models of very low metallicity, e.g., $Z = 0.0001$ ($[Fe/H] \sim -2.3$), to observations of fluorine in CEMP stars, which likely achieved their chemical peculiarities from an AGB companion. Schuler et al. (2007) observed $[F/Fe] = 2.90$ in one such star with a $[Fe/H] = -2.5$. The $2 M_{\odot}$, $Z = 0.0001$ model reached a fluorine production factor of ~ 3.59 , which translates into a huge $[F/Fe] = 3.63$. This may be enough to explain the observations of Schuler et al. (2007), although we need to consider dilution due to binary mass transfer. The fact that fluorine

production shows a strong dependence on the initial stellar mass (see, for example, Fig. 1 of Lugaro et al. 2004) suggests that we may use the detailed model predictions along with observations of the lowest metallicity stars to provide constraints on the properties of the initial mass function in the early universe (see, for example, Tumlinson 2007).

7. CONCLUSIONS

In conclusion, the comparison of our results to observations of $[F/O]$ in AGB stars, and to the Ne composition of SiC grains suggests that the values of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction rate may lie closer to the current upper limit. More experimental data for this reaction at temperatures below 0.4 GK are, however, required to help verify this result. The result for F in AGB stars is less compelling than the results for Ne in SiC grains, owing to the fact that we cannot match the whole observed $[F/O]$ range. Adding to this problem is the need for some extramixing process to alter the C and N abundances while not destroying ^{19}F . In addition, AGB modeling uncertainties (e.g., mass loss and molecular opacities) could dramatically affect the predictions of F yields and surface abundances, rendering any conclusions uncertain.

The modeling uncertainties related to extramixing, the TDU, and mass loss do not affect, however, the intershell compositions of our stellar models and thus do not apply to the discussion of the Ne composition of stellar SiC grains. From Figure 2 and the related discussion, we see that the measured Ne isotopic compositions could be explained by the upper limit for the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction. This tantalizing result is also a more reliable hint that the reaction is indeed closer to its upper limit than the comparison to F in AGB stars. However, further work is required to test this scenario, including a detailed investigation into Kr nucleosynthesis in AGB stars.

Finally, the larger stellar yields of ^{19}F obtained using the upper limit of the $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ reaction should be tested in a galactic chemical evolution model of the type presented by Renda et al. (2004). An AGB contribution to the production of ^{21}Ne may also be considered, given that the upper limit of the $^{18}\text{F}(\alpha, p)$ rate results in a larger production of this rare Ne isotope. The observations of low F abundances in stars in the globular cluster ω Centauri by Cunha et al. (2003), where other observations clearly indicate pollution by AGB stars (e.g., Stanford et al. 2007), are puzzling. Clearly further work is required to address the nucleosynthetic origin of this most interesting and fragile element.

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