GALACTIC CHEMICAL EVOLUTION AND SOLAR s-PROCESS ABUNDANCES: DEPENDENCE ON THE $^{13}$C-POCKET STRUCTURE

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ABSTRACT

We study the $s$-process abundances ($A \gtrsim 90$) at the epoch of the solar system formation. Asymptotic giant branch yields are computed with an updated neutron capture network and updated initial solar abundances. We confirm our previous results obtained with a Galactic chemical evolution (GCE) model: (1) as suggested by the $s$-process spread observed in disk stars and in presolar meteoritic SiC grains, a weighted average of $s$-process strengths is needed to reproduce the solar $s$ distribution of isotopes with $A > 130$; and (2) an additional contribution (of about 25%) is required in order to represent the solar $s$-process abundances of isotopes from $A = 90$ to 130. Furthermore, we investigate the effect of different internal structures of the $^{13}$C pocket, which may affect the efficiency of the $^{13}$C($\alpha$, $n$)$^{16}$O reaction, the major neutron source of the $s$ process. First, keeping the same $^{13}$C profile adopted so far, we modify by a factor of two the mass involved in the pocket; second, we assume a flat $^{13}$C profile in the pocket, and we test again the effects of the variation of the mass of the pocket. We find that GCE $s$ predictions at the epoch of the solar system formation marginally depend on the size and shape of the $^{13}$C pocket once a different weighted range of $^{13}$C-pocket strengths is assumed. We obtain that, independently of the internal structure of the $^{13}$C pocket, the missing solar system $s$-process contribution in the range from $A = 90$ to 130 remains essentially the same.

Key words: stars: AGB and post-AGB – Galaxy: evolution – Sun: abundances

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The solar system abundances result from contributions of different nucleosynthesis processes. Isotopes heavier than the iron group are produced via neutron captures—the slow and the rapid processes ($s$ and $r$). Exceptions include the 35 or so $s$-isotopes synthesized by the $p$ process.

The origin of the $r$ process is currently attributed to explosive nucleosynthesis in massive stars, even if the astrophysical conditions are still not well defined (see, e.g., Thielemann et al. 2011). The $p$ process is identified with photo-disintegration processes (the so-called $\gamma$ process; Howard et al. 1991) of heavy elements occurring in core collapse supernovae of Type II (e.g., Rauscher et al. 2002; Hayakawa et al. 2008). Accreting white dwarfs in binary systems with masses approaching the Chandrasekhar limit may substantially contribute to the production of $p$-process nuclei when they explode as Type Ia supernovae (e.g., Travaglio et al. 2011 and references therein).

Concerning the $s$ process, pioneering studies (Seeger et al. 1965; Clayton & Rassbach 1967) have demonstrated that the solar $s$ distribution of isotopes from iron to bismuth may be reproduced by three components: the weak, the main, and the strong components. The weak component contributes to $s$ isotopes up to $A \sim 90$, and it takes place in massive stars during core He and convective shell C burning (see, e.g., Pignatari et al. 2010; Frischknecht et al. 2012). The main component ($A \sim 90$–208) is derived from low mass asymptotic giant branch (AGB) stars during their thermally pulsing (TP) phase (Arlandini et al. 1999; Busso et al. 1999; Goriely & Mowlavi 2000; Cristiano et al. 2009; Bisterzo et al. 2011; Lugaro et al. 2012). The strong component is needed to reproduce about half of solar $^{208}$Pb, and it originates from AGB stars of low metallicity (at [Fe/H] $\sim -1$; Gallino et al. 1998; Travaglio et al. 2001; Van Eck et al. 2001).

After a limited number of TPs, at the quenching of recurrent thermal instabilities in the He shell, the convective envelope penetrates in the outer region of the He intershell (third dredge-up, TDU), bringing to the surface newly synthesized $^{12}$C and $s$-process isotopes. The whole envelope undergoes strong mass loss by stellar winds, leaving the degenerate core that eventually will become a white dwarf.

The major neutron source of the $s$ process in low mass AGB stars ($M < 4\, M_\odot$) is the $^{13}$C($\alpha$, $n$)$^{16}$O reaction, which is activated in radiative conditions during the interpulse phase (Straniero et al. 1995). At the quenching of a TDU, a small amount of hydrogen is assumed to penetrate from the envelope into the top layers of the radiative He-rich zone. At hydrogen re-ignition, a thin $^{13}$C pocket forms by proton captures on the abundant $^{12}$C. When the temperature of $\sim 9 \times 10^9$ K is reached (which corresponds to $kT \sim 8$ keV), $^{13}$C is fully depleted, releasing neutrons with a density of about $10^7$ n cm$^{-3}$.

The $^{13}$C in the pocket is of primary origin, directly synthesized in the star from the $^{12}$C produced by partial He burning during previous thermal pulse and is independent of the initial composition. However, the number of free neutrons per iron seed increases with decreasing metallicity. Consequently, for a given $^{13}$C-pocket strength, the $s$-process flow first feeds the $s$-process peak Sr–Y–Zr (at magic neutron number $N = 50$), extending up to $^{136}$Ba, then reaches the second $s$-process peak.
(Ba–La–Pr–Ce–Nd at $N = 82$), extending up to $^{204}$Pb–$^{207}$Pb, with a progressive increasing ratio of the heavy $s$ elements (hs) to the light $s$ elements (ls). At even lower metallicity, it mainly feeds $^{208}$Pb ($N = 126$) at the end of the $s$-process path. Therefore, the $s$ process in AGB stars is strongly metallicity dependent. The complexity of the $s$-process distribution in AGB stars is confirmed by spectroscopic observations in different stellar populations (planetary nebulae, post-AGB, MS, S, C(N), Ba, CH, and CEMP $s$ stars; see, e.g., Smith & Lambert 1990; Pêquignot & Baluteau 1994; Aoki et al. 2002; Abia et al. 2002; Allen & Barbey 2006; Jonsell et al. 2006; Sharpee et al. 2007; Sterling & Dinerstein 2008; Reyniers et al. 2007; Zamora et al. 2009). Furthermore, for a given metallicity a spread in the $s$-process distribution is observed for each class of stars. A range of 13C-pocket strengths is needed in order to explain this spread (see, e.g., Busso et al. 2001; Sneden et al. 2008; Käppeler et al. 2011; Bisterzo et al. 2011; Lugaro et al. 2012). A similar spread is shown by $s$-process isotopic signatures found in presolar meteoritic SiC grains, which originated in the outflow of AGB stars (see, e.g., Lugaro et al. 2003; Clayton & Nittler 2004; Zimmer 2007).

A marginal activation of the $^{22}$Ne$(\alpha,n)^{25}$Mg reaction occurs at the bottom of the advanced convective thermal pulses, where a temperature of $T \sim 3 \times 10^8$ K is reached. A short neutron burst is released with a peaked neutron density (up to $N_n \sim 10^{11}$ n cm$^{-3}$), which provides only a few percent of the total neutron exposure but affects the abundances of some important isotopes close to the main branchings of the $s$ process (e.g., $^{85}$Kr and $^{95}$Zr, sensitive to neutron density).

For an extended review on the $s$ process, we refer to Käppeler et al. (2011) and references therein.

Several model uncertainties affect the AGB yields, e.g., the mass loss efficiency, the deepness of the TDU, and the number of TPs (Herwig 2005; Straniero et al. 2006). In AGB modeling, the formation of the 13C pocket and the physical prescriptions involved are particularly challenging. Iben & Renzini (1983) suggested that, as a consequence of the TDU, a sharp discontinuity between the H-rich envelope and the He- and C-rich intershell forms and a partial mixing of protons from the envelope into the He intershell may take place. The amount of protons that diffuse into the He intershell must be small to allow the production of 13C and to limit the further conversion of 13C to 14N by proton captures; 14N mainly acts as a neutron poison of the $s$ process via the $^{14}$N$(n,p)^{13}$C reaction. In the external zone of the pocket (where protons are more abundant), a 14N-rich zone may also form, depending on the proton profile adopted in the AGB model; this region plays a minor role in the $s$-process nucleosynthesis.

The hydrogen profile and, correspondingly, the internal structure of the 13C pocket may depend on the initial mass and metallicity of the AGB and on the physical mechanisms that may compete inside the star itself. Herwig et al. (1997) proposed an exponential diffusive overshooting at the borders of all convective zones. FRUITY models by Cristallo et al. (2009, 2011) adopted an opacity-induced overshooting at the base of the convective envelope by introducing in the model an exponentially decaying profile of the convective velocity. Starting from Langer et al. (1999), Herwig et al. (2003), and Siess et al. (2004), rotation was introduced in stellar models to study its impact on the 13C-pocket structure. The first studies agree that rotation-induced instabilities reduce the total mass of 13C in the pocket, owing to the 14N contamination in the 13C-rich layer, compromising the $s$-process efficiency. Piersanti, Cristallo, & Straniero (2013) confirm that rotation-induced instabilities modify the mass extension of both 13C and 14N abundances in the pocket, as well as their overlap. Moreover, they suggest that meridional (Eddington–Sweet) circulation may smooth and enlarge the 13C-rich zone of the pocket.

Denissenkov & Tout (2003) demonstrated that a weak turbulence induced by gravity waves presents an additional alternative for the 13C-pocket formation. On the other hand, Busso et al. (2012) revisit the idea that rotation favors mixing indirectly, through the maintenance of magnetic dynamo mechanisms, producing the buoyancy of toroidal magnetic structures (Busso et al. 2007; see also Maiorca et al. 2012 for results in young open clusters).

Further investigations on rotation, magnetic fields, gravity waves, and the interplay between these several mechanisms will help to shed light on this challenging issue.

The solar system $s$-process distribution is the result of the nucleosynthesis of all previous generations of AGB stars that have polluted the interstellar medium. Therefore, a Galactic chemical evolution (GCE) model is required to follow the complex evolutionary processes of the Milky Way. Travaglio et al. (1999) showed that AGB yields computed within a weighted average over the range of 13C pockets are needed in the framework of a GCE model to reproduce the $s$ distribution observed in the solar system. This is also suggested by the spectroscopic $s$-process spread observed in individual stars and the isotopic anomalies measured in presolar SiC grains.

GCE calculations succeeded in reproducing the solar abundances of $s$-only isotopes between $^{134}$Ba and $^{208}$Pb (Travaglio et al. 2001, 2004). However, a deficit (of about 25%) between GCE predictions at the solar epoch and the abundances measured in the solar system was found for Sr, Y, Zr, and $s$-process isotopes up to $A = 130$, including 10 $s$-only isotopes from $^{96}$Mo to $^{130}$Xe (see also Käppeler et al. 2011; their Figure 15). The weak $s$ process produces isotopes up to Sr ($\sim$10% for Sr and $\lesssim$5% for Y and Zr isotopes), with a negligible contribution afterwards. An additional $r$ fraction of $\sim$10% was estimated for solar Sr–Y–Zr, evaluating the $r$ contribution from the prototypical r-II star CS 22892–052.7 In summary, the $s$ and $r$ (and $p$) contributions predicted by current stellar models are not sufficient to explain the solar abundances of light isotopes from $A = 90$ to 130. Travaglio et al. (2004) hypothesized the existence of an additional process of unknown origin that the authors called LEPP (light-element primary process), which must supply $\sim$8% of solar Sr and $\sim$18% of solar Y and Zr. Several scenarios have been recently explored, involving a primary component in massive stars that comes from the activation of $^{13}$C$(\alpha,n)^{16}$O in the C core when the temperature is low enough to prevent the $^{13}$N$(\gamma,p)^{12}$C reaction from becoming efficient (defined as “cold” C-burning component or $cs$ component by Pignatari et al. 2013) and/or a light $r$ process induced by explosive stellar nucleosynthesis, e.g., in the neutrino-driven winds (Arcones & Thielemann 2013 and references therein).

The aim of this work is to investigate the influence of one of the major AGB yield uncertainties, the formation of the 13C pocket, on the predicted solar $s$-process distribution, from light neutron capture isotopes (to verify the need of LEPP) up to Pb and Bi at the end of the $s$ path. First, in Section 2, we present updated $s$ percentages for isotopes from Kr to Bi with respect to Travaglio et al. (2004). In Section 3, we test the effect of AGB

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7 CS 22892–052 has an $s$-process enrichment of $\sim$40 times the solar scaled composition ([Eu/Fe] = 1.6; Sneden et al. 2003).
yields computed with different choices of the internal structure of the $^{13}$C pocket on GCE at predictions at the epoch of the solar system formation. Our results are briefly summarized in Section 4.

2. UPDATED SOLAR $s$ ABUNDANCES PREDICTED BY GCE

2.1. The Galactic Chemical Evolution Model

The general structure of the GCE model adopted in this work is the same described by Travaglio et al. (2004). The GCE model follows the composition of stars, stellar remnants, interstellar matter (atomic and molecular gas), and their mutual interaction, in the three main zones of the Galaxy, halo, thick disk, and thin disk. We concentrate on the chemical evolution inside the solar annulus, located 8.5 kpc from the Galactic center. The thin disk is divided into independent concentric annuli, and we neglect any dependence on Galactocentric radius.

The chemical evolution is regulated by the star formation rate (SFR), initial mass function (IMF), and nucleosynthesis yields from different stellar mass ranges and populations. The SFR has been determined self-consistently as the result of aggregation, which are interacting and interchanging processes of the interstellar gas that may occur spontaneously or stimulated by the presence of other stars. The stellar contributions from different mass ranges or from single and binary stars are treated separately: we distinguish between single low- and intermediate-mass stars ending their life as a He or C–O white dwarf ($0.8 M_{\odot} \leq M < 8 M_{\odot}$), single massive stars exploding as Type II supernovae (SNeII), $8 M_{\odot} \leq M \leq 100 M_{\odot}$), and binary stars that give rise to Type Ia supernova (SNIa) events. SFR and IMF are the same as adopted by Travaglio et al. (2004).

In Figure 1 (top panel), the SFR rate in the three Galactic zones is displayed versus [Fe/H]. Galactic halo and thick disk are assumed to form on a relatively short timescale: after only $<0.5$ Gyr the metallicity increases up to [Fe/H] $\sim 0.5$ (halo phase), to reach [Fe/H] $\sim 1.0$ faster than in 2 Gyr. The thin-disk phase in our GCE model starts after ~1 Gyr, at [Fe/H] $\sim 0.5$. The corresponding [O/Fe] versus [Fe/H] is shown in Figure 1 (bottom panel), together with an updated compilation of observational data (see caption). Because oxygen is mainly synthesized by short-lived SNeII, and under the hypothesis that Fe is mostly produced by long-lived SNeIa ($\sim$-one-third by SNeIa and $\sim$-two-thirds by SNeIa), the presence of a knee in the trend of [O/Fe] versus [Fe/H] indicates the delayed contribution to iron by SNeIa.

We refer to Travaglio et al. (2004 and references therein) for more details on the adopted GCE model.

The GCE is computed as function of time up to the present epoch ($t_{\text{Today}} = 13.8$ Gyr, updated by WMAP; Spergel et al. 2003; Bennett et al. 2013). Given that the solar system formation occurred 4.6 Gyr ago, the Galactic time corresponding to the birth of the solar system is $t_{\odot} = 9.2$ Gyr, about 0.7 Gyr later than found by Travaglio et al. (2004). This temporal shift has been achieved by slightly reducing the Fe contribution by SNeIa.

Solar abundances have been updated according to Lodders et al. (2009), while Travaglio et al. (2004) adopted solar values by Anders & Grevesse (1989).

Stellar yields by Rauscher et al. (2002) and Travaglio et al. (2004a) are used for SNeIa and SNeIa, respectively. A detailed description of the AGB yields adopted in this work is given in Section 2.2.
case ST × 2 corresponds to an upper limit, because further proton ingestion leads to the formation of 14N at expenses of 13C. The minimum 13C pocket that significantly affects the s distribution depends on the initial iron content of the star, given that the number of neutrons available per iron seeds increases with decreasing metallicity. As a minimum 13C pocket, we assume case ST × 0.1 at disk metallicities and case ST × 0.03 in the halo (see discussion by Bisterzo et al. 2010, 2011). LMS models of $M = 1.3, 1.4, 1.5,$ and $2M_\odot$ have been computed by following the interpolation formulae given by Straniero et al. (2003) for $-1.0 \leq [\text{Fe}/\text{H}] \leq 0.0$ and then further extrapolating the stellar parameters from $[\text{Fe}/\text{H}] = +0.2$ down to $[\text{Fe}/\text{H}] = -3.6$ as described by Bisterzo et al. (2010). Note that for $M = 1.3 M_\odot$ models, the conditions for the activation of the TDU episodes are never reached for metallicities higher than $[\text{Fe}/\text{H}] \sim -0.6$ (Straniero et al. 2003), and we compute $1.3 M_\odot$ yields starting from $[\text{Fe}/\text{H}] = -0.6$ down to $-3.6$.

Starting from Domínguez et al. (1999; see also Boothroyd & Sackmann 1988), it was shown that, for a given initial mass, the core mass increases with decreasing metallicity and AGB models with $M \gtrsim 3 M_\odot$ and $[\text{Fe}/\text{H}] \sim -1.3$ are not far from the transition zone between LMS and IMS stars. As discussed by Bisterzo et al. (2010), we have assumed that AGB stars with $M = 3 M_\odot$ should behave as IMS for $[\text{Fe}/\text{H}] \lesssim -1.6$. Thus, our $3 M_\odot$ models have been been computed by extrapolating the stellar parameters from $3 M_\odot$ models by Straniero et al. (2003) in the metallicity interval between $-1.6 \leq [\text{Fe}/\text{H}] \leq +0.2$.

We recall that low metallicity IMS stars may be affected by an extremely efficient dredge-up called hot TDU (Herwig 2004), which may influence the structure of the star and its evolution. Because nucleosynthesis models that include hot TDU are still subject of study, we have computed IMS yields only for $[\text{Fe}/\text{H}] \gtrsim -1.6$ (Bisterzo et al. 2010).

IMS models are based on full evolutionary AGB models by Straniero et al. (2000). Their 5.0 $M_\odot$ models at $[\text{Fe}/\text{H}] = 0$ and $-1.3$ show comparable characteristics, e.g., temperature during TPs, TDU, and He-intershell masses. Thus, we have assumed that the structure of 5.0 $M_\odot$ models from $[\text{Fe}/\text{H}] = +0.2$ down to $[\text{Fe}/\text{H}] = -1.6$ are barely distinguishable from solar. Solar 5 and $7 M_\odot$ models described by Straniero et al. (2000) have comparable He-intershell mass and temperature at the bottom of the TPs, while the TDU mass is a factor of $\sim 6$ lower in 7 $M_\odot$ model. Starting from these stellar characteristics, we have extrapolated the 7.0 $M_\odot$ models in the metallicity range between $-1.6 \leq [\text{Fe}/\text{H}] \leq +0.2$.

The treatment of mass loss in IMS models is largely uncertain (see, e.g., Ventura & D’Antona 2005b), and the number of TPs with TDU experienced by IMS stars may vary by a factor of three or more, affecting the structure and nucleosynthesis of the star itself. With the efficient mass loss adopted in our IMS models, AGB with $M = 5$ and $7 M_\odot$ experience 24 TPs followed by TDU (Bisterzo et al. 2010).

IMS AGB stars play a minor role in the Galactic enrichment of s-process isotopes, with the exception of a few neutron-rich isotopes as $^{86}\text{Kr}, ^{87}\text{Rb},$ and $^{96}\text{Zr}$ (Travaglio et al. 2004). Indeed, the mass of the He intershell is about a factor of 10 lower in IMS than in LMS. Thus, the overall amount of material dredged into the envelope of IMS decreases by at least one order of magnitude with respect to LMS (Straniero et al. 2000). Moreover, IMS experience hot bottom burning during the interpulse phase: the bottom of the convective envelope reaches the top of the H-burning shell and the temperature at the base is large enough ($T \gtrsim 4 \times 10^7$ K) to activate the CN cycle, thus converting $^{12}\text{C}$ to $^{13}\text{N}$ (see, e.g., Karakas & Lattanzio 2003; Ventura & D’Antona 2005a). Hot bottom burning may even inhibit the formation of the $^{13}$C pocket in IMS of low metallicity (Goriely & Siess 2004; Herwig 2004). As a consequence, the $^{13}$C($e, n$)16O neutron source is expected to have a small or even negligible effect on neutron capture isotopes heavier than $A \sim 90$. On the basis of these considerations, new AGB IMS yields have been computed with a negligible $^{13}$C pocket. The introduction of a small $^{13}$C pocket ($M(13C) = 10^{-7} M_\odot$), as assumed in the old IMS models adopted by Travaglio et al. (2004), has negligible effects on solar s-process predictions (see Section 2.3).

On the other hand, a higher temperature is reached at the bottom of the TPs of IMS ($T \sim 3.5 \times 10^8$ K), so that the $^{22}\text{Ne} (\alpha, n) ^{25}\text{Mg}$ reaction is efficiently activated. Because of the high peak neutron density ($N_n \sim 10^{12}$ n cm$^{-3}$), $^{86}\text{Kr}, ^{87}\text{Rb},$ and $^{96}\text{Zr}$ are strongly overproduced, owing to the branchings at $^{85}\text{Kr}, ^{86}\text{Rb},$ and $^{95}\text{Zr}$. The observational evidence of the strong activation of the $^{22}\text{Ne} (\alpha, n) ^{25}\text{Mg}$ reaction (associated to IMS) is the excess of Rb with respect to Zr (see, e.g., Lambert et al. 1995; Tomkin & Lambert 1999; Abia et al. 2001, and most recently Yong et al. 2008; García-Hernández et al. 2009, 2013; D’Orazi et al. 2013). The high $[\text{Rb}/\text{Zr}]$ observed in some OH/IR AGB stars seems to be incompatible with IMS predictions. Karakas et al. (2012) proposed that delayed supernovae may increase the number of TPs and thus the $[\text{Rb}/\text{Fe}]$ and $[\text{Rb}/\text{Zr}]$ predictions. A complementary possibility to solve the mismatch observed and predicted $[\text{Rb}/\text{Zr}]$ in OH/IR AGB stars has been suggested by García-Hernández et al. (2009) and van Raai et al. (2012), who discussed how model atmospheres of luminous pulsating AGB stars may be incomplete and $[\text{Rb}/\text{Fe}]$ may be overestimated.

Given the present uncertainties, our 5 and $7 M_\odot$ models may experience a larger number of TPs under the hypothesis of a less efficient mass loss. However, the resulting effect on solar s-process predictions is marginal (with the exception of the neutron-rich isotopes $^{86}\text{Kr}, ^{87}\text{Rb},$ and $^{96}\text{Zr}$; see Section 2.3), because the solar s contribution from LMS stars dominates over IMS.

In IMS with initial mass of $M \sim 6$–$8 M_\odot$, the temperature at the base of the convective envelope further increases ($T \gtrsim 1 \times 10^8$ K), leading to a greater degree of proton-capture nucleosynthesis that efficiently activates CNO, NeNa, and MgAl cycles as well. These more massive AGB stars, ending as Ne–O SAGB, may be incomplete and [Rb/Zr] predictions. A complementary possibility to solve the mismatch observed and predicted [Rb/Zr] in OH/IR AGB stars has been suggested by García-Hernández et al. (2009) and van Raai et al. (2012), who discussed how model atmospheres of luminous pulsating AGB stars may be incomplete and [Rb/Fe] may be overestimated.

8 For example, circumstellar dust envelope and dust formation and 3D hydrodynamical simulations are not included; NLTE effects are not considered.
from previous AGB generations starting from [Fe/H] ≳−1.6 (see Travaglio et al. 2004; Serinato et al. 2009). Thus, AGB models with a more refined grid of 20 metallicities have been computed between [Fe/H] = −1.6 and 0.9.

Similarly, about three hundred 3 $M_\odot$ models have been run between [Fe/H] = −1.6 up to +0.2, for a range of 13C pockets and a total of 20 metallicities. Forty M = 5 and 7 $M_\odot$ models with a negligible 13C pocket have been calculated between [Fe/H] = −1.6 up to +0.2, for 20 metallicities in total.

Linear interpolations/extrapolations over the whole mass AGB range (1.3 ≤ $M/M_\odot$ < 8, with mass steps of 0.1 $M_\odot$) have been carried out for AGB yields not explicitly calculated. With respect to Travaglio et al. (2004), we have introduced new AGB models of initial masses 1.3, 1.4, and 2 $M_\odot$.

All AGB yields have been computed with an updated neutron capture network according to the online database KADoNiS10 and more recent measurements: 92,94,96Zr (Tagliente et al. 2010, 2011a, 2011b), 186,187,188Os (Mosconi et al. 2010), and the p-only 180W (Marganiec et al. 2010), as well as 41K and 45Sc (Heit et al. 2009), 24,25,26Mg (Massimi et al. 2012), 63Ni (Lederer et al. 2013), and 64,67Zn (Reifarth et al. 2012), among light isotopes that marginally affect the $s$-process contribution. Note that we employed Mutti et al. (2005) for 80,82,83,84,86Kr, Patronis et al. (2004) for 136,137Cs, Reifarth et al. (2003) for 148,149Pm, and Best et al. (2001) for 152,154Eu.

Furthermore, AGB initial abundances are scaled to the updated solar values by Lodders et al. (2009).

2.3. Discussion of the Results

The $s$-process GCE predictions at the epoch of the solar system formation are displayed in Figure 2 as percentages of the abundances by Lodders et al. (2009). The $s$-only isotopes are represented by solid circles. Different symbols have been used for 96Zr (big asterisk), 186Ta (empty circle), which also receives contributions from the $p$ process and from neutrino–nucleus interactions in massive stars, and 187Os (empty triangle), which is affected by the long-lived decay of 187Re (4.1 × 10^{10} yr). We distinguish 208Pb, which is produced at ∼50% of LMS of low metallicity, with a big filled square.

In the framework of GCE, we have considered a weighted average among the various 13C-pocket strengths (see Section 1). Observations of $s$-process rich stars at disk metallicity (see, e.g., Käppeler et al. 2011; their Figure 12) suggest that most of them lie in the range between case ST × 1.5 down to ST/1.5. Very few stars can be interpreted by case ST × 2. Actually, for 13C pockets below case ST/6 the $s$ enhancement becomes negligible. We exclude case ST × 2 from the average of the 13C pockets, and we give a weight of ∼25% to case ST × 1.3. The unbranched $s$-only 150Sm can be taken as reference isotope for the whole $s$-process distribution, because its solar abundance is well defined (5% uncertainty as a rare earth element, “REE”) and the neutron capture cross section is given at 1%.

A complete list of $s$-process percentages of all isotopes and elements from Kr to Bi is given in Table 1, where updated GCE results are compared with previous GCE predictions by Travaglio et al. (2004). The theoretical $s$-process predictions by Travaglio et al. (2004) were normalized to solar abundances by Anders & Grevesse (1989). The $s$ percentages of LMS, IMS, and the total $s$ contribution (LMS + IMS) are reported for GCE results by Travaglio et al. (2004; Columns 3, 4, and 5) and this work (Columns 6, 7, and 8). Values in column 8 correspond to those displayed in Figure 2. In comparison to GCE results, we list in Column 2 the main $s$ process contributions by Bisterzo et al. (2011), obtained as in Arlandini et al. (1999) by averaging between AGB models of $M = 1.5$ and $3 M_\odot$ and half solar metallicity.

The variations between GCE results by Travaglio et al. (2004) and those computed in this work (see Table 1) are partly due to the updated nuclear reaction network and new solar abundances.

The solar abundance distribution is essentially based on CI carbonaceous chondrite measurements in terrestrial laboratories with increasingly accurate experimental methods. Among the exceptions are volatile elements such as CNO, which are evaluated from photospheric determinations, or noble gases such as Ne, evaluated from solar corona winds. Kr and Xe solar abundances are derived theoretically from neutron-capture element systematics (Palme & Beer 1993; Reifarth et al. 2002). Since 1989, C, N, and O abundances have been steadily revised downward thanks to progress in atmospheric models (see, e.g., Asplund 2005), partially affecting the isotopic mass fraction of heavier isotopes. Moreover, the photospheric abundances observed today are different from those existing at the beginning of the solar system (4.6 Gyr ago), because of the element settling from the solar photosphere into the Sun’s interior. Lodders et al. (2009) found that original protosolar values of elements heavier than He (Z were ∼13% larger than observed today (whereas He increases by about ∼15%).

In Figure 3, we show updated GCE results normalized to solar abundances by Lodders et al. (2009; black symbols) and Anders & Grevesse (1989; gray symbols; as made by Travaglio et al. 2004). Noteworthy solar abundance variations (−10%) are CNO (∼−30%), P (∼−20%), S (∼−25%), Cl (+37%), Kr (+24%), Nb (+13%), I (+22%), Xe (+16%), and Hg (+35%).

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9 Twelve metallicities between [Fe/H] = −1.6 and −0.6 have been run for 1.3 $M_\odot$ models.

10 Karlsruhe Astrophysical Data Base of Nucleosynthesis in Stars, Web site http://www.kadonis.org/; version v0.3.

Note that about half of solar Z abundances (where Z is the sum of all elements heavier than helium, called “metals” in stars) comes from oxygen, followed by carbon, neon, and nitrogen (as well as silicon, magnesium, and iron).

12 Variations refer to values normalized to the number of silicon atoms N(Si) = 10^6.
Additional differences between the GCE results shown in Table 1 are derived from experimental cross section measurements and theoretical nuclear improvements provided in the last decade.

New GCE calculations include the recent theoretical evaluation of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate by Longland et al. (2012), which is based on the direct experimental measurement by Jaeger et al. (2001). At AGB temperatures ($T_{\text{eff}} \sim 2.5$–3.5), the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate by Longland et al. (2012) is very close to the value by Jaeger et al. (2001), and it is about a factor of two lower than the rate we used so far: the lowest limit by Käppeler et al. (1994). The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ neutron source produces variations of the $s$ isotopes close to the branching points: updated GCE calculations have reduced the $s$ contribution to few light isotopes, $^{86}\text{Kr}$, $^{87}\text{Rb}$, and $^{96}\text{Zr}$ (and the $s$-only $^{96}\text{Mo}$), with a complementary increase of $^{86,87}\text{Sr}$, owing to the branches at $^{86}\text{Kr}$, $^{87}\text{Rb}$, and $^{95}\text{Zr}$. Minor effects (<10%) are seen for heavier isotopes (see Bisterzo et al. 2013; Figure 1, bottom panel). A discussion of the major branching points of the $s$ process and the effect of the new $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ rate will be given in S. Bisterzo et al. (in preparation).

The total $s$ production of $^{96}\text{Zr}$ obtained in 2004 (~80%) was particularly large. Updated GCE results predict that about half of solar $^{96}\text{Zr}$ comes from AGB stars (~3% from IMS and ~36% from LMS; see Table 1). Travaglio et al. (2011) estimated an additional non-negligible $p$-process contribution to $^{96}\text{Zr}$ by SNeLa (up to 30%).

However, we remind that $^{96}\text{Zr}$ is strongly sensitive to the $^{95}\text{Zr}(n, \gamma)^{96}\text{Zr}$ rate, which is largely uncertain when being evaluated only theoretically. In this regard, we adopt a rate roughly half the value recommended by Bao et al. (2000), close to that by Toukan & Käppeler (1990), and in agreement with Zr isotopic measurements in presolar SiC grains (Lugaro et al. 2003). Recently, Lugaro et al. (2014) provide a lower estimation of the $^{95}\text{Zr}(n, \gamma)^{96}\text{Zr}$ rate: at $kT \sim 23$ keV, their value is roughly three times lower than that by Bao et al. (2000) and about half of that by Toukan & Käppeler (1990). This results in a decreased GCE $s$ contribution to solar $^{96}\text{Zr}$ by ~10%.

Moreover, $^{96}\text{Zr}$ depends on the number of TPs experienced by the adopted AGB models. Our LMS models with $M = 1.5$, 2, and $3 M_\odot$ experience several TPs with TDU, from 20 to 35 TPs depending on the mass and metallicity (Bisterzo et al. 2010, their Table 2), reaching temperatures high enough to partly activate the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ neutron source and to open the branch at $^{96}\text{Zr}$. A stronger mass loss would partly reduce the $s$ contribution to $^{96}\text{Zr}$ from LMS AGB stars.

On the other hand, our $M = 5$ and $7 M_\odot$ models experience 24 TPs. Given the large uncertainty affecting the treatment of mass loss in IMS (Section 2.2), the number of TPs may increase by a factor of three or more (in particular for $M = 7 M_\odot$ models), leading to a greater overall amount of material dredged up. Owing to the dominant $s$ contribution from LMS stars over IMS, the general effect on solar GCE prediction would be negligible even by increasing the mass of the TDU in both $M = 5$ and $7 M_\odot$ models several times. Exceptions are $^{95}\text{Zr}$, $^{86}\text{Rb}$, and $^{96}\text{Zr}$, which receive a non-negligible contribution from IMS stars: by increasing the TDU mass of IMS by a factor of six, the solar prediction to $^{96}\text{Zr}$ increases from ~40% up to ~60%; similar variations affect $^{86}\text{Kr}$ (~20%), and larger effects are show $^{87}\text{Rb}$ (from ~30% up to ~70%).

As discussed in Section 2.2, new IMS yields are computed with a negligible $^{13}\text{C}$ pocket; instead, Travaglio et al. (2004) assumed that a $^{13}\text{C}$ pocket with $M(13\text{C})$ = $10^{-7} M_\odot$ could form in IMS, yielding an increase of ~10% to solar $^{96}\text{Zr}$, ~3% to $^{86}\text{Kr}$, and ~6% to $^{96}\text{Rb}$. Solar GCE predictions of isotopes with $A > 100$ show marginal variations, because the $^{13}\text{C}$-pocket contribution from IMS is almost negligible (up to a few percent) when compared with that of LMS.

New neutron capture cross-section measurements further modify the $s$-process distribution. Travaglio et al. (2004) adopted the compilation by Bao et al. (2000), while we refer to KADoNiS (as well as few additional measurements listed above). Important variations come from the new $^{139}\text{La}(n, \gamma)^{140}\text{La}$ rate by Winckler et al. (2006), the $^{180}\text{Ta}(n, \gamma)^{181}\text{Ta}$ rate by Wisshak et al. (2004; including the revised stellar enhancement factor, SEF, by KADoNiS), and the improved treatment of the branch at $^{176}\text{Lu}$, which modifies the $^{176}\text{Lu}/^{176}\text{Hf}$ ratio (Heil et al. 2008). The solar $s$ contribution to La, often used as a reference element to disentangle between $s$- and $r$-process enrichment in the atmosphere of peculiar stars, increases by ~40% (from 63% to 76%, see Table 1). The solar $s$ production of $^{180}\text{Ta}$ increases from ~50% to ~80%, substantially reducing the contribution expected from the $p$ process.

Discrepancies of ~10% for $^{154}\text{Gd}$ and $^{166}\text{Dy}$ and ~20% for $^{192}\text{Pt}$ (see Section 2.4) suggest that large uncertainties affect the neutron capture cross sections at stellar energy (e.g., SEF evaluation) for isotopes with $A > 150$. Note that $^{160}\text{Dy}$ may receive a small contribution from the $p$ process (Travaglio et al. 2011). Despite all Pb isotopes having well-determined neutron capture cross sections (see KADoNiS), the contribution to the $s$-only $^{204}\text{Pb}$ is affected by the branch at $^{204}\text{Tl}$, which produces variations of ~10%.

Finally, as recalled above, the new GCE predictions adopt an extended range of AGB yields, including $M = 1.3$, 1.4, and $2 M_\odot$ models. In Travaglio et al. (2004), only $M = 1.5$ and $3 M_\odot$ models among LMS were used for GCE calculations.

AGB stars with initial mass of $M = 1.3$ and $1.4 M_\odot$ experience 5 and 10 TPs followed by TDU, respectively (Bisterzo et al. 2010). This results in an additional $s$-process contribution of
Table 1
Solar s-process Contributions (in %) for Isotopes from Kr to Bi Obtained with GCE Model

| Isotope | Main-s\[^a\] | Solar s-process Distribution [T04] | Solar s-process Distribution [This work] |
|---------|-------------|-----------------------------------|----------------------------------------|
|         |             | LMS (3)  | IMS (4)  | (3)+(4) (5) | LMS (6)  | IMS (7)  | (6)+(7) (8) |
|         |             |          |          |            |          |          |            |
| 80Kr[^c\| 7.9 | 13.56 | 4.06 | 17.6 | 12.77 | 0.52 | 13.3 |
| 82Kr | 23.8 | 36.93 | 15.15 | 52.1 | 25.64 | 1.79 | 27.4 |
| 83Kr | 9.0 | 12.28 | 4.85 | 17.1 | 8.92 | 0.62 | 9.5 |
| 84Kr | 11.7 | 12.18 | 5.35 | 17.5 | 10.95 | 0.77 | 11.7 |
| 86Kr[^c\| 16.2 | 21.49 | 33.96 | 55.4 | 11.65 | 3.58 | 15.2 |
| Kr[^b\ | 13.4 | 16.66 | 11.31 | 28.0 ± 5.0 | 12.55 | 1.35 | 13.9 ± 2.9 |
| 85Rb[^b\ | 18.3 | 13.66 | 8.51 | 22.2 | 13.68 | 1.62 | 15.3 |
| 87Rb[^c\ | 29.3 | 27.33 | 49.50 | 55.4 | 11.65 | 3.58 | 15.2 |
| Rb[^b\ | 21.5 ± 1.5 | 17.65 | 20.47 | 38.1 ± 2.6 | 14.92 | 3.19 | 18.1 ± 1.6 |
| 86Sr[^c\ | 59.2 | 43.17 | 8.42 | 51.6 | 59.29 | 1.85 | 61.1 |
| 87Sr | 97.3 ± 6.8 | 60.70 | 9.13 | 69.8 ± 5.7 | 67.52 | 1.35 | 68.9 ± 5.9 |
| Sr[^b\ | +3.0%[^b\ | 60.89 | 7.43 | 68.3 | 70.64 | 1.29 | 71.9 |
| Y[^c\ | +3.0% ± 10.3[^d\ | 60.89 | 7.43 | 68.3 ± 4.2 | 70.64 | 1.29 | 71.9 ± 8.0 |
| 90Zr[^f\ | 84.8 | 46.83 | 6.14 | 53.0 | 59.59 | 0.73 | 60.3 |
| 91Zr[^c\ | +5.5%[^d\ | 61.49 | 17.62 | 79.1 | 69.52 | 1.64 | 71.2 |
| 92Zr[^c\ | 59.7 | 48.12 | 5.15 | 53.3 | 57.06 | 1.19 | 58.2 |
| 94Zr[^c\ | +25.5%[^d\ | 70.20 | 8.51 | 78.7 | 82.70 | 0.89 | 83.6 |
| 96Zr[^c\ | 53.1 | 46.83 | 6.14 | 53.0 | 59.59 | 0.73 | 60.3 |
| Zr[^b\ | 96.0 ± 9.6 | 54.61 | 10.31 | 64.9 ± 4.2 | 65.27 | 1.06 | 66.3 ± 7.4 |
| 93Nb[^c\ | 85.6 | 54.65 | 11.49 | 66.1 | 54.93 | 1.09 | 56.0 |
| 95Nb | 85.6 ± 8.6 | 54.65 | 11.49 | 66.1 ± 1.3 | 54.93 | 1.09 | 56.0 ± 6.3 |
| 94Mo[^c\ | 0.9 | 0.59 | 0.00 | 0.6 | 0.95 | 0.00 | 1.0 |
| 95Mo | 69.6 | 34.36 | 4.16 | 38.5 | 45.00 | 0.45 | 45.4 |
| 96Mo[^c\ | +19.9%[^d\ | 69.60 | 7.72 | 77.3 | 77.43 | 0.79 | 78.2 |
| 97Mo | 63.7 | 39.60 | 5.74 | 45.3 | 42.77 | 0.51 | 43.3 |
| 98Mo[^c\ | 82.2 | 52.28 | 6.24 | 58.5 | 56.96 | 0.52 | 57.5 |
| 99Mo[^c\ | 4.5 | 1.98 | 0.40 | 2.4 | 2.27 | 0.03 | 2.3 |
| Mo[^c\ | 57.7 ± 5.8 | 33.85 | 4.06 | 37.9 ± 2.1 | 38.34 | 0.38 | 38.7 ± 4.3 |
| 99Ru[^c\ | 33.1 | 19.60 | 2.28 | 21.9 | 20.78 | 0.18 | 21.0 |
| 100Ru[^c\ | +9.9%[^d\ | 65.35 | 6.73 | 72.1 | 79.56 | 0.59 | 80.1 |
| 101Ru | 17.7 | 10.40 | 1.09 | 11.5 | 12.67 | 0.09 | 12.8 |
| 102Ru | 50.0 | 28.91 | 2.67 | 31.6 | 43.07 | 0.27 | 43.3 |
| 104Ru[^c\ | 2.5 | 1.49 | 0.10 | 1.6 | 1.44 | 0.01 | 1.4 |
| Ru[^c\ | 37.3 ± 2.2 | 21.91 | 2.19 | 24.1 ± 1.3 | 28.69 | 0.20 | 28.9 ± 2.3 |
| 103Rh[^c\ | 15.2 | 9.11 | 0.79 | 9.9 | 11.76 | 0.07 | 11.8 |
| Rh[^c\ | 15.2 ± 1.5 | 9.11 | 0.79 | 9.9 ± 0.8 | 11.76 | 0.07 | 11.8 ± 1.3 |
| 104Pd[^c\ | +21.6%[^d\ | 70.69 | 6.04 | 76.7 | 83.41 | 0.46 | 83.9 |
| 105Pd | 15.7 | 9.11 | 0.79 | 9.9 | 10.64 | 0.06 | 10.7 |
| 106Pd | 58.4 | 34.06 | 2.77 | 36.8 | 39.63 | 0.20 | 39.8 |
| 108Pd | 74.6 | 43.37 | 3.27 | 46.6 | 50.27 | 0.24 | 50.5 |
| 110Pd | 3.0 | 1.88 | 0.20 | 2.1 | 1.62 | 0.01 | 1.6 |
| Pd[^c\ | 53.1 ± 2.7 | 30.91 | 2.50 | 33.4 ± 2.2 | 35.99 | 0.18 | 36.2 ± 2.6 |
| 107Ag[^c\ | 16.6 | 0.40 | 0.00 | 0.4 | 0.05 | 0.00 | 0.1 |
| 109Ag | 28.1 | 16.73 | 1.29 | 18.0 | 22.50 | 0.11 | 22.6 |
| Ag[^c\ | 22.1 ± 1.1 | 8.26 | 0.62 | 8.9 ± 0.3 | 10.86 | 0.05 | 10.9 ± 0.8 |
| 108Cd[^c\ | 0.4 | 0.20 | 0.00 | 0.2 | 1.12 | 0.00 | 1.1 |
| 110Cd[^c\ | +15.1%[^d\ | 65.15 | 4.65 | 69.8 | 77.23 | 0.35 | 77.6 |
| 111Cd | 38.0 | 15.84 | 1.09 | 16.9 | 24.83 | 0.11 | 24.9 |
| 112Cd | 74.8 | 35.45 | 2.48 | 37.9 | 49.66 | 0.22 | 49.9 |
Table 1
(Continued)

| Isotope | Main-s$^a$ | Solar s-process Distribution [T04] | Solar s-process Distribution [This work] |
|---------|------------|----------------------------------|----------------------------------------|
|         | (1)        | LMS (3) | IMS (4) | (3)+(4) (5) | LMS (6) | IMS (7) | (6)+(7) (8) |
| $^{113}$Cd | 43.2 | 23.37 | 1.58 | 25.0 | 28.38 | 0.12 | 28.5 |
| $^{114}$Cd | 89.8 | 43.17 | 2.77 | 45.9 | 58.88 | 0.25 | 59.1 |
| $^{116}$Cd | 17.0 | 9.60 | 1.39 | 11.0 | 8.67 | 0.09 | 8.8 |
| Cd | 69.6 ± 4.9 | 34.70 | 2.41 | 37.1 ± 2.5 | 45.85 | 0.20 | 46.1 ± 4.0 |
| $^{113}$In$^b$ | 0.0 | 0.00 | 0.00 | 0.0 | 0.01 | 0.00 | 0.0 |
| $^{115}$In | 44.3 | 24.75 | 1.58 | 26.3 | 29.69 | 0.12 | 29.8 |
| In | 42.4 ± 3.0 | 23.69 | 1.52 | 25.2 ± 1.6 | 28.42 | 0.12 | 28.5 ± 2.5 |
| $^{114}$Sn$^b$ | 0.0 | 0.00 | 0.00 | 0.0 | 0.07 | 0.00 | 0.1 |
| $^{116}$Sn | 96.2 | 59.60 | 3.47 | 63.1 | 68.00 | 0.27 | 68.3 |
| $^{117}$Sn | 56.9 | 33.37 | 1.98 | 35.3 | 38.21 | 0.15 | 38.4 |
| $^{118}$Sn | 80.6 | 50.89 | 3.47 | 63.1 | 68.00 | 0.27 | 68.3 |
| $^{119}$Sn | 65.3 | 58.51 | 3.27 | 61.8 | 64.23 | 0.23 | 62.7 |
| $^{122}$Sn | 46.6 | 38.02 | 8.61 | 46.6 | 35.98 | 0.47 | 36.4 |
| Sn | 73.2 ± 11.0 | 46.75 | 2.97 | 49.7 ± 4.7 | 52.27 | 0.22 | 52.5 ± 8.3 |
| $^{121}$Sb | 41.4 | 28.12 | 1.58 | 29.7 | 30.81 | 0.11 | 30.9 |
| $^{123}$Sb | 6.5 | 4.75 | 0.99 | 5.7 | 4.91 | 0.05 | 5.0 |
| Sb | 26.4 ± 4.0 | 18.12 | 1.33 | 19.5 ± 3.5 | 19.73 | 0.09 | 19.8 ± 3.1 |
| $^{122}$Te | 97.2 | 66.44 | 3.66 | 70.1 | 73.38 | 0.26 | 73.6 |
| $^{123}$Te | 97.3 | 68.12 | 3.76 | 71.9 | 73.88 | 0.27 | 74.1 |
| $^{124}$Te | 0.3%$^d$ | 71.29 | 4.65 | 75.9 | 77.83 | 0.31 | 78.1 |
| $^{125}$Te | 2.2 | 15.74 | 1.09 | 16.8 | 17.33 | 0.07 | 17.4 |
| $^{126}$Te | 44.9 | 32.87 | 2.08 | 35.0 | 36.18 | 0.14 | 36.3 |
| $^{128}$Te | 3.8 | 1.39 | 0.10 | 1.5 | 3.25 | 0.01 | 3.3 |
| Te | 19.6 ± 1.4 | 13.57 | 0.86 | 14.4 ± 1.5 | 15.51 | 0.06 | 15.6 ± 1.3 |
| $^{127}$I | 4.7 | 4.26 | 0.30 | 4.6 | 3.78 | 0.01 | 3.8 |
| I | 4.7 ± 1.0 | 4.26 | 0.30 | 4.6 ± 1.0 | 3.78 | 0.01 | 3.8 ± 0.8 |
| $^{128}$Xe | 81.1 | 66.83 | 4.16 | 71.0 | 76.01 | 0.28 | 76.3 |
| $^{129}$Xe | 2.8 | 2.57 | 0.20 | 2.8 | 2.76 | 0.01 | 2.8 |
| $^{130}$Xe | 88.1 | 68.81 | 4.16 | 73.0 | 84.83 | 0.29 | 85.1 |
| $^{131}$Xe | 6.7 | 5.35 | 0.30 | 5.6 | 6.46 | 0.02 | 6.5 |
| $^{132}$Xe | 27.1 | 28.42 | 1.58 | 30.0 | 26.76 | 0.08 | 26.8 |
| $^{134}$Xe | 3.6 | 5.25 | 1.98 | 7.2 | 3.97 | 0.08 | 4.1 |
| Xe | 15.4 | 14.37 | 1.00 | 15.4 ± 3.1 | 15.03 | 0.06 | 15.1 ± 3.1 |
| $^{133}$Cs | 15.6 | 12.28 | 0.69 | 13.0 | 13.48 | 0.04 | 13.5 |
| Cs | 15.6 ± 0.8 | 12.28 | 0.69 | 13.0 ± 0.7 | 13.48 | 0.04 | 13.5 ± 1.0 |
| $^{134}$Ba | +12.5%$^d$ | 88.22 | 4.16 | 92.4 | +0.64%$^d$ | 0.25 | +0.9%$^d$ |
| $^{135}$Ba | 30.2 | 22.18 | 1.58 | 23.8 | 28.38 | 0.11 | 28.5 |
| $^{136}$Ba | +13.7%$^d$ | 91.19 | 4.06 | 95.2 | +1.04%$^d$ | 0.27 | +1.3%$^d$ |
| $^{137}$Ba | 67.3 | 62.28 | 9.41 | 71.7 | 62.63 | 0.58 | 63.2 |
| $^{138}$Ba | 94.2 | 83.17 | 2.48 | 85.6 | 91.72 | 0.10 | 91.8 |
| Ba | 88.7 ± 5.3 | 77.38 | 3.35 | 80.7 ± 5.2 | 85.03 | 0.17 | 85.2 ± 6.7 |
| $^{139}$La | 71.0 | 60.79 | 1.68 | 62.5 | 75.40 | 0.07 | 75.5 |
| La | 71.1 ± 3.6 | 60.79 | 1.68 | 62.5 ± 1.5 | 75.40 | 0.07 | 75.5 ± 5.3 |
| $^{140}$Ce | 89.5 | 80.20 | 1.49 | 81.7 | 91.92 | 0.05 | 92.0 |
| $^{142}$Ce | 19.3 | 23.76 | 2.77 | 26.5 | 19.46 | 0.07 | 19.5 |
| Ce | 81.3 ± 4.1 | 73.58 | 1.62 | 75.2 ± 1.6 | 83.47 | 0.05 | 83.5 ± 5.9 |
| $^{141}$Pr | 51.7 | 46.83 | 0.89 | 47.7 | 49.86 | 0.03 | 49.9 |
| Pr | 51.7 ± 3.6 | 46.83 | 0.89 | 47.7 ± 1.3 | 49.86 | 0.03 | 49.9 ± 4.3 |
| $^{142}$Nd | 97.6 | 89.31 | 0.99 | 90.3 | 98.31 | 0.04 | 98.3 |
| $^{143}$Nd | 32.7 | 30.89 | 0.69 | 31.6 | 32.84 | 0.02 | 32.9 |
Table 1
(Continued)

| Isotope | Main-s<sup>a</sup> | Solar s-process Distribution [T04] | Solar s-process Distribution [This work] |
|---------|-------------------|----------------------------------|------------------------------------------|
|         | LMS (1) | IMS (2) | (3)+(4) | LMS (5) | IMS (6) | (7) | (6)+(7) |
| 144Nd   | 52.2    | 49.41   | 1.19    | 50.6    | 52.19   | 0.03 | 52.2    |
| 145Nd   | 26.3    | 26.73   | 0.69    | 27.4    | 26.15   | 0.02 | 26.2    |
| 148Nd   | 57.3    | ±2.9    | 50.0    | 53.48   | ±1.0    | 57.51 | 0.03    | 57.5 ±4.1 |
| 147Sm   | 26.2    | 20.00   | 0.50    | 20.5    | 26.45   | 0.02 | 26.5    |
| 149Sm   | 12.6    | 12.18   | 0.30    | 12.5    | 12.87   | 0.01 | 12.9    |
| 152Sm   | 100.0   | 97.13   | 2.77    | 99.9    | 99.93   | 0.07 | 100.0   |
| 148Gd   | 23.1    | 22.18   | 0.69    | 22.9    | 22.80   | 0.02 | 22.8    |
| 151Eu   | 6.0     | 6.34    | 0.20    | 6.5     | 5.87    | 0.00 | 5.9     |
| 153Eu   | 7.4     | 6.95    | 0.10    | 6.0     | 6.13    | 0.00 | 6.1     |
| Eu      | 6.0     | ±0.3    | 0.15    | 5.8 ±0.1 | 6.01    | 0.00 | 6.0 ±0.4 |
| 152Gd<sup>c</sup> | 70.5 | 85.74 | 1.49 | 87.2 | 86.55 | 0.04 | 86.6 |
| 154Gd   | 88.0    | 93.07   | 2.57    | 95.6    | 89.08   | 0.07 | 89.1    |
| 156Gd   | 16.9    | 16.53   | 0.50    | 17.0    | 17.84   | 0.01 | 17.9    |
| 157Gd   | 10.6    | 10.40   | 0.30    | 10.7    | 11.05   | 0.01 | 11.1    |
| 159Gd   | 27.1    | 26.63   | 0.79    | 27.4    | 27.46   | 0.02 | 27.5    |
| 159Tb   | 8.4     | 7.03    | 0.20    | 7.2     | 7.96    | 0.01 | 8.0     |
| Tb      | 8.4     | ±0.6    | 0.20    | 7.2 ±0.2 | 7.96    | 0.01 | 8.0 ±0.7 |
| 160Dy   | 91.3    | 98.12   | 3.07    | +1.2%<sup>d</sup> | 90.00 | 0.07 | 90.1 |
| 161Dy   | 5.2     | 5.25    | 0.20    | 5.4     | 5.27    | 0.00 | 5.3     |
| 162Dy   | 16.0    | 14.55   | 0.50    | 15.0    | 16.01   | 0.01 | 16.0    |
| 163Dy   | 4.3     | 3.47    | 0.10    | 3.6     | 4.41    | 0.00 | 4.4     |
| 164Dy   | 23.0    | 16.34   | 0.59    | 16.9    | 23.92   | 0.02 | 23.9    |
| Dy      | 14.8    | ±0.7    | 0.43    | 12.9 ±0.2 | 15.03 | 0.01 | 15.0 ±1.1 |
| 165Ho   | 8.1     | 7.43    | 0.20    | 7.6     | 8.34    | 0.01 | 8.3     |
| Ho      | 8.1     | ±0.6    | 0.20    | 7.6 ±0.2 | 8.34    | 0.01 | 8.3 ±0.7 |
| 164Er<sup>c</sup> | 74.5 | 80.20 | 2.38 | 82.6 | 83.31 | 0.06 | 83.4 |
| 166Er   | 15.9    | 14.26   | 0.50    | 14.8    | 16.72   | 0.01 | 16.7    |
| 167Er   | 9.2     | 8.32    | 0.30    | 8.6     | 9.43    | 0.01 | 9.4     |
| 168Er   | 28.6    | 27.72   | 0.99    | 28.7    | 31.42   | 0.03 | 31.4    |
| 170Er   | 12.3    | 5.64    | 0.30    | 5.9     | 12.57   | 0.01 | 12.6    |
| Er      | 18.2    | ±0.9    | 0.58    | 16.9 ±0.3 | 19.44 | 0.02 | 19.5 ±1.4 |
| 169Tm   | 12.2    | 12.97   | 0.50    | 13.5    | 9.13    | 0.01 | 9.1     |
| Tm      | 12.2    | ±0.9    | 12.97   | 0.50    | 13.5 ±0.4 | 9.13 | 0.01 | 9.1 ±0.8 |
| 170Yb   | 90.6    | 100.00  | 3.17    | +3.2%<sup>d</sup> | 95.77 | 0.07 | 95.8 |
| 171Yb   | 20.9    | 13.47   | 0.50    | 14.0    | 22.70   | 0.02 | 22.7    |
| 172Yb   | 43.9    | 29.31   | 0.99    | 30.3    | 43.88   | 0.04 | 43.9    |
| 173Yb   | 26.9    | 20.69   | 0.69    | 21.4    | 27.77   | 0.02 | 27.8    |
| 174Yb   | 60.5    | 48.02   | 1.68    | 49.7    | 60.81   | 0.05 | 60.9    |
| 176Yb   | 8.2     | 10.50   | 0.69    | 11.2    | 7.23    | 0.01 | 7.2     |
| Yb      | 39.9    | ±2.0    | 31.31   | 1.12    | 32.4 ±0.7 | 40.46 | 0.03 | 40.5 ±2.9 |
| 175Lu   | 17.8    | 17.13   | 0.59    | 17.7    | 18.04   | 0.02 | 18.1    |
| 176Lu   | +1.2%<sup>d</sup> | +33.66%d | 3.96  | +37.6%d | +5.40%d | 0.12 | +5.54%d |
| Lu      | 20.2    | ±1.0    | 20.42   | 0.69    | 21.1 ±0.4 | 20.50 | 0.02 | 20.5 ±1.5 |
| 176Hf   | 97.3    | 93.37   | 3.07    | 96.4    | +0.03%d | 0.07 | +0.13%d |
| Hf      | 17.2    | 17.72   | 0.69    | 18.4    | 17.33   | 0.01 | 17.3    |
| Isotope | Main-s* | Solar s-process Distribution [T04] | Solar s-process Distribution [This work] |
|--------|---------|-----------------------------------|----------------------------------|
|        | (1)     | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 178Hf  | 58.5    | 55.05 | 1.98 | 57.0 | 57.46 | 0.05 | 57.5 |
| 179Hf  | 41.0    | 35.54 | 1.29 | 36.8 | 41.15 | 0.04 | 41.2 |
| 180Hf  | 88.8    | 73.07 | 2.77 | 75.8 | 89.29 | 0.08 | 89.4 |
| Hf     | 61.0 ± 3.1 | 53.68 | 1.98 | 55.7 ± 1.3 | 61.07 | 0.05 | 61.1 ± 4.3 |
| 180Ta  | 75.5    | 46.93 | 1.49 | 48.4 | 81.99 | 0.05 | 82.0 |
| Ta     | 46.5    | 40.00 | 1.51 | 41.5 | 46.52 | 0.04 | 46.6 |
| 180Wc  | 5.1     | 4.65 | 0.10 | 4.8 | 4.52 | 0.00 | 4.5 |
| W      | 46.5 ± 4.7 | 40.00 | 1.51 | 41.5 ± 0.9 | 46.52 | 0.04 | 46.6 ± 5.2 |
| 180Os  | +11.6%d | 97.52 | 3.17 | +0.7%d | +3.37%d | 0.09 | +3.53%d |
| 187Os  | 39.9    | 42.28 | 2.67 | 45.0 | 37.40 | 0.03 | 37.4 |
| 188Os  | 29.6    | 18.51 | 0.69 | 19.2 | 28.17 | 0.03 | 28.2 |
| 189Os  | 4.5     | 4.16 | 0.20 | 4.4 | 4.81 | 0.01 | 4.8 |
| 190Os  | 14.6    | 11.58 | 0.50 | 12.1 | 14.59 | 0.02 | 14.6 |
| 191Os  | 3.5     | 0.89 | 0.00 | 0.9 | 3.30 | 0.00 | 3.3 |
| Os     | 12.3 ± 1.0 | 8.67 | 0.34 | 9.0 ± 0.6 | 11.88 | 0.01 | 11.9 ± 1.1 |
| 190Ir  | 2.0     | 1.78 | 0.10 | 1.9 | 1.92 | 0.00 | 1.9 |
| 191Ir  | 1.3     | 0.99 | 0.00 | 1.0 | 1.42 | 0.00 | 1.4 |
| Ir     | 1.6 ± 0.1 | 1.29 | 0.04 | 1.3 ± 0.1 | 1.60 | 0.00 | 1.6 ± 0.1 |
| 192Pt  | 87.1    | 98.22 | 3.37 | +1.6%d | 81.08 | 0.08 | 81.2 |
| 194Pt  | 6.6     | 3.86 | 0.10 | 4.0 | 4.93 | 0.01 | 4.9 |
| 195Pt  | 2.6     | 1.58 | 0.10 | 1.7 | 2.00 | 0.00 | 2.0 |
| 196Pt  | 13.2    | 9.41 | 0.30 | 9.7 | 12.26 | 0.01 | 12.3 |
| 198Pt  | 0.0     | 0.00 | 0.00 | 0.0 | 0.09 | 0.00 | 0.1 |
| Pt     | 7.1 ± 0.6 | 4.95 | 0.17 | 5.1 ± 0.4 | 6.04 | 0.01 | 6.0 ± 0.6 |
| 197Au  | 5.9     | 5.64 | 0.20 | 5.8 | 6.05 | 0.01 | 6.1 |
| Au     | 5.9 ± 0.6 | 5.64 | 0.20 | 5.8 ± 0.9 | 6.05 | 0.01 | 6.1 ± 0.7 |
| 198Hg  | 82.6    | 100.00 | 3.37 | +3.4%d | 82.70 | 0.09 | 82.8 |
| 199Hg  | 21.7    | 25.84 | 0.89 | 26.7 | 21.59 | 0.02 | 21.6 |
| 200Hg  | 52.4    | 62.77 | 1.98 | 64.8 | 51.89 | 0.05 | 51.9 |
| 201Hg  | 39.7    | 47.13 | 1.49 | 48.6 | 39.83 | 0.04 | 39.9 |
| 202Hg  | 65.3    | 78.02 | 2.28 | 80.3 | 70.33 | 0.08 | 70.4 |
| 204Hg  | 8.0     | 9.21 | 0.00 | 9.2 | 8.18 | 0.01 | 8.2 |
| Hg     | 49.3 ± 9.9 | 58.97 | 1.82 | 60.8 ± 7.3 | 50.69 | 0.05 | 50.7 ± 10.5 |
| 203Tl  | 83.1    | 72.08 | 2.18 | 74.3 | 80.57 | 0.09 | 80.7 |
| 205Tl  | 62.8    | 75.15 | 1.98 | 77.1 | 66.69 | 0.06 | 66.7 |
| Tl     | 68.8 ± 5.5 | 74.24 | 2.04 | 76.3 ± 7.2 | 70.79 | 0.07 | 70.9 ± 6.7 |
| 204Pb  | 96.7    | 92.87 | 2.57 | 95.4 | 86.85 | 0.10 | 87.0 |
| 206Pb  | 66.6    | 61.88 | 1.39 | 63.3 | 72.87 | 0.07 | 72.9 |
| 207Pb  | 57.8    | 80.00 | 1.39 | 81.4 | 70.13 | 0.05 | 70.2 |
| 208Pb  | 41.6    | 92.67 | 1.19 | 93.9 | 97.70 | 0.04 | 97.7 |
| Pb     | 50.7 ± 3.6 | 84.35 | 1.29 | 85.6 ± 6.8 | 87.20 | 0.05 | 87.2 ± 7.5 |
| 209Bi  | 6.3     | 18.22 | 0.59 | 18.8 | 20.37 | 0.03 | 20.4 |
| Bi     | 6.3 ± 0.6 | 18.22 | 0.59 | 18.8 ± 1.6 | 20.37 | 0.03 | 20.4 ± 2.1 |
about 5% and 10% at the epoch of the solar system, without modifying the $s$ distribution. Note that for metallicities higher than [Fe/H] $\sim -0.6$, $M = 1.3 \, M_\odot$ models do not contribute to the chemical evolution of the Galaxy because the conditions for the activation of the TDU episodes are never reached in our models (see Straniero et al. 2003).

The addition of $M = 2 \, M_\odot$ yields in GCE computations provides an increase of about 10% of the predicted solar $^{208}$Pb, and smaller variations to isotopes with $A \lesssim 140$ (lower than 5%), with the exception of solar $^{96}$Zr (which is 10% lower). AGB stars with $M = 1.5$ and $2 \, M_\odot$ predict comparable $s$-process abundances because both models reach similar temperatures during convective TPs and the larger overall amount of material dredged up by the $2 \, M_\odot$ model (which experiences about six more TDU than the $1.5 \, M_\odot$ model) is diluted with a more extended envelope (Bisterzo et al. 2010). Thus, in both 1.5 and 2 $M_\odot$ models the marginal activation of the $^{22}$Ne($\alpha$, $n$)$^{25}$Mg produces a smaller $s$ process contribution to the first $s$ peak (including $^{96}$Zr) than in 3 $M_\odot$ models, while on average $^{208}$Pb is favored, being that the $^{13}$C($\alpha$, $n$)$^{16}$O reaction is the main source of neutrons. Instead, AGB stars with an initial mass of $M = 3 \, M_\odot$ and [Fe/H] $\sim -1$ reach higher temperatures at the bottom of the TPs ($T_\beta = 3.5$), feeding more efficiently the first and second $s$ peaks than $^{208}$Pb. As a consequence, linear interpolations between $M = 1.5$ and $3 \, M_\odot$ yield, as previously made by Travaglio et al. (2004), induced up to 10% differences in $^{96}$Zr and $^{208}$Pb solar predictions.

Updated GCE calculations plausibly interpret within the nuclear and solar uncertainties all $s$-only isotopes with $A > 130$.

The understanding of the origin of light $s$-process isotopes with $A \lesssim 130$ remains enigmatic: we confirm the missing $\sim 25\%$ predicted solar $s$ contribution to isotopes from $^{86}$Sr to $^{130}$Xe (including the $s$-only, $^{96}$Mo, $^{100}$Ru, $^{104}$Pd, $^{110}$Cd, $^{116}$Sn, $^{122,123,124}$Te, and $^{128,130}$Xe) first found by Travaglio et al. (2004). Few of them may receive an additional small contribution from the $p$ process (e.g., 2% to $^{96}$Mo, 5% to $^{110}$Cd, 3% to $^{122}$Te, and 6% to $^{128}$Xe; Travaglio et al. 2011).

In Section 3, we explore the effect of the $^{13}$C-pocket uncertainty in LMS on GCE predictions at the epoch of the solar system formation.

2.4. New Neutron Capture Rates for $^{192}$Pt and $^{192}$Ir Isotopes

The solar $s$-only $^{192}$Pt predicted by the GCE model is about 20% lower than measured in the solar system. So far, we considered this value plausible within the known uncertainties; the KADoNiS recommended $^{192}$Pt($n$, $\gamma$)$^{193}$Pt rate has 20% of uncertainty ($390 \pm 120$ mbarn at 30 keV; Bao et al. 2000), the neutron capture cross sections of $^{191}$Os and $^{192}$Ir are evaluated theoretically at 22%, and the solar Pt abundance is known with 8% of uncertainty (Lodders et al. 2009).

Recently, Koehler & Guber (2013) measured the neutron capture cross sections of Pt isotopes with much improved accuracy and used their experimental results to provide a new theoretical estimation of the $^{192}$Ir($n$, $\gamma$) rate. The new Maxwellian-Averaged Cross Sections (MACS) of $^{192}$Pt($n$, $\gamma$)$^{193}$Pt ($483 \pm 20$ mbarn at 30 keV; 4% uncertainty) is $\sim 20\%$ lower than that recommended by KADoNiS, suggesting an increased $^{192}$Pt prediction ($\sim 90\%$), which in better agreement with the solar value. On the other hand, the theoretical $^{192}$Ir($n$, $\gamma$) rate estimated by Koehler & Guber (2013) is much larger (about +50%) than that by KADoNiS ($2080 \pm 450$ mbarn at 30 keV), reducing again the $s$ contribution to $^{192}$Pt.

The new GCE prediction of solar $^{192}$Pt obtained by including neutron capture rates of Pt isotopes and $^{192}$Ir by Koehler & Guber (2013) is $\sim 78\%$. This value may increase up to $\sim 85\%$ by considering the uncertainty of the theoretical $^{192}$Ir($n$, $\gamma$) rate ($\pm 22\%$) and up to 93% by adopting a $2\sigma$ uncertainty.

More detailed analyses on $^{192}$Ir MACS would help to improve the understanding of this branching point and to provide a more accurate solar $^{192}$Pt estimation (e.g., Rauscher 2012).

3. EFFECT OF THE $^{13}$C-POCKET UNCERTAINTY IN LMS ON GCE PREDICTIONS AT THE EPOCH OF THE SOLAR SYSTEM FORMATION

As discussed in Section 1, the problem of the formation of the $^{13}$C pocket is still unsolved. The tests on the $^{13}$C pocket discussed in this work allow us to explore the impact of different shapes and sizes of the adopted $^{13}$C pocket on the $s$ process yields.

The internal structure of the $^{13}$C pocket adopted so far is specified in Table 2 (first group of data): it is a three-zone $^{13}$C pocket (zones I, II, and III roughly correspond to those described by Gallino et al. 1998, their Figure 1), each one has defined $X(^{13}$C) and $X(^{14}$N) abundances and a total $^{13}$C mass of $\sim 5 \times 10^{-9} \, M_\odot$ $\sim 2 \times 10^{-9} \, M_\odot$ of $^{14}$N). The total mass of the three-zone pocket is about the 20th part of a typical convective TP in LMS ($M($pocket$) \sim 0.001 \, M_\odot$). This corresponds to the so-called case ST. As anticipated in Section 2.2, case ST is calibrated to reproduce the solar main component (Arlandini et al. 1999).

Note that case ST differs from a H profile that exponentially decreases starting from the envelope value $X(H) = 0.7$. In such


**Table 2** Internal Structure of the $^{13}$C-pockets Adopted in the Tests Displayed in Figure 5.

| Zone | M(pocket) | M1 | M2 | M3 |
|------|-----------|----|----|----|
| Zone I | M(pocket) = 1.09E−3 M⊙ | 5.50E−4 | 5.30E−4 | 7.50E−6 |
| Zone II | X(13C) = 3.20E−3 | 6.80E−3 | 1.60E−2 |
| Zone III | X(14N) = 1.07E−4 | 2.08E−4 | 2.08E−3 |

**TEST A**: three-zone model with M(pocket) = 2 × 1.09E−3 M⊙

| Mass(M⊙) | M1 | M2 | M3 |
|-----------|----|----|----|
| Mass(M⊙) | 1.06E−3 | 1.06E−3 | 1.50E−5 |
| X(13C) | 3.20E−3 | 6.80E−3 | 1.60E−2 |
| X(14N) | 1.07E−4 | 2.08E−4 | 2.08E−3 |

**TEST B**: three-zone model with M(pocket) = 0.5 × 1.09E−3 M⊙

| Mass(M⊙) | M1 | M2 | M3 |
|-----------|----|----|----|
| Mass(M⊙) | 2.75E−4 | 2.65E−4 | 3.75E−6 |
| X(13C) | 3.20E−3 | 6.80E−3 | 1.60E−2 |
| X(14N) | 1.07E−4 | 2.08E−4 | 2.08E−3 |

**TEST C**: zone-II model with M(pocket) = 5.30E−4 M⊙

| Mass(M⊙) | M1 | M2 | M3 |
|-----------|----|----|----|
| Mass(M⊙) | 5.30E−4 | 6.30E−4 | 7.30E−4 |
| X(13C) | 6.80E−3 | 1.60E−2 |
| X(14N) | 2.08E−4 | 2.08E−3 |

**TEST D**: zone-II model with M(pocket) = 2 × 5.30E−4 M⊙

| Mass(M⊙) | M1 | M2 | M3 |
|-----------|----|----|----|
| Mass(M⊙) | 1.06E−3 | 1.06E−3 | 1.50E−5 |
| X(13C) | 6.80E−3 | 1.60E−2 |
| X(14N) | 2.08E−4 | 2.08E−3 |

Notes. First, we specify the mass and the amount of $^{13}$C and $^{14}$N in the three-zone $^{13}$C-pocket adopted so far (case ST with zones I-II-III; M(pocket) = 1.09E−3 M⊙; represented with filled circles). In TEST A and B, we leave the $^{13}$C profile unchanged, but we multiply and divide by a factor of two the mass of the pocket (M(pocket) = 2 × 1.09E−3 M⊙; displayed with filled triangles; M(pocket) = 0.5 × 1.09E−3 M⊙; displayed with filled down-rotated triangles). Under the hypothesis that only the flat profile of zone II of our standard $^{13}$C-pocket form (zone-II model, with flat $^{13}$C and $^{14}$N abundances), we provide two additional tests in which we change the mass involved in the pocket: TEST C with M(pocket) = 5.30E−4 M⊙ (empty circles) and TEST D with M(pocket) = 2 × 5.30E−4 M⊙ (empty squares).

As a first test, we increase the mass of the pocket by a factor of two, keeping unchanged the amount of $^{13}$C and $^{14}$N in the three zones of the $^{13}$C pocket (see Figure 4, filled triangles). For comparison we also represent with filled circles the $s$-process distribution shown in Figure 2. Intuitively, if we adopt the same weighted average of the various $^{13}$C-pocket strengths as performed before, one should obtain an overestimation by a factor of two of the whole $s$-process abundance distribution. Effectively, we predict 200% of solar $^{136}$Ba, 230% of solar $^{150}$Sm, and 300% of solar $^{208}$Pb. We already recalled that, in order to reconcile GCE predictions with solar abundances, we have the freedom to change the weighted average among the various $^{13}$C-pocket strengths: specifically, we exclude case ST × 1.3 from the $^{13}$C-pocket average, and we reduce the weight of case ST to 20% (see Figure 5, filled triangles). This may be justified in the framework of the observed $s$-process spread, which, within the large degree of current AGB model uncertainties, we compute with a range of $^{13}$C-pocket strengths.

As a second test, we reduce the mass of the three-zone $^{13}$C pocket by a factor of two (see Figure 4, filled down-rotated triangles). The predicted solar $s$ contributions are reduced to 48% of solar $^{136}$Ba, 43% of solar $^{150}$Sm, and 37% of solar $^{208}$Pb. As shown in Figure 5 (filled down-rotated triangles), this underestimation can be solved by fully including case ST × 1.3 (which in our standard GCE calculation is considered at ~25%, Section 2.3) in the $^{13}$C-pocket average.

As a consequence, an increased or decreased mass of the $^{13}$C pocket by a factor of two in all LMS models marginally affects the predicted solar $s$-process distribution obtained with a weighted average of $^{13}$C-pocket strengths. Analogous results are obtained by further increasing the mass of the $^{13}$C pocket.

Similar solutions are achieved by the two additional tests computed with flat $^{13}$C profiles (see Figure 5): zone-II $^{13}$C pockets with M(pocket) ~ 0.0005 M⊙ (empty circles) and M(pocket) ~ 0.001 M⊙ (empty squares), which corresponds to the mass of zone II of our standard pocket multiplied by a factor of two. By giving different weights to cases ST × 1.3 and ST, which dominate the average of $^{13}$C-pocket strengths, the solar $s$ distribution predicted by the GCE model shows variations within the solar uncertainties: ~5% for $s$-only isotopes from $A = 140$ to $210$ and $A = 100$ to $125$, and up to ~5% for $^{134,136}$Ba and $^{128,130}$Xe. More evident variations (~10%) are displayed by few isotopes lighter than $A = 100$, e.g., $^{86,87}$Sr.
and $^{90}$Zr, which, however, receive an additional contribution by other astrophysical sources (e.g., weak $s$ process, $p$ process).

The deficit of the predicted solar $s$ abundances for isotopes from $A = 90$ to 130 remains unchanged with the tests shown in Figure 5.

In summary, according to an $s$ distribution referred to $^{150}$Sm, the need of an additional $s$ process between $A = 90$ and 130 (LEPP-$s$, given that $s$-only isotopes also show the missing contribution) is confirmed by updated GCE results. Specifically, the need of LEPP-$s$ is independent of the most significant $^{13}$C-pocket tests we carried out in this paper.

This result supports the presence of an $s$ process in massive stars during the pre-explosive phases that follow the core He-burning and convective shell C-burning phases. According to Pignatari et al. (2010), the weak $s$ process may produce Sr–Y–Zr in larger amounts (up to ~30%) than previously estimated by Raiteri et al. (1992; <10%). However, while the weak $s$ contribution estimated for lighter trans-iron elements (e.g., Cu) is plausibly established because they are weakly affected by uncertainties of nuclear rates, C shell evolution, neutron density history, or initial composition, heavier isotopes such as Sr show larger sensitivity to stellar models and nuclear uncertainties. Recent investigations suggest that the $s$ contribution from massive stars may extend to heavier elements, with a bulk of the production at Sr–Y–Zr and, in a minor amount, up to Te–Xe (Pignatari et al. 2013).

4. CONCLUSIONS

We study the solar abundances of heavy $s$ isotopes at the epoch of the formation of the solar system as the outcome of nucleosynthesis occurring in AGB stars of various masses and metallicities. At present, one of the major uncertainties of AGB stellar model is the formation of the $^{13}$C pocket. Our aim is to investigate the impact of uncertainties concerning the internal structure of the $^{13}$C pocket on the GCE $s$ distribution, by carrying out different tests in which we modify the $^{13}$C and $^{14}$N abundances in the pocket and the size in mass of the pocket itself.

Thereby, we find that GCE $s$-process predictions at the epoch of the solar system formation marginally depend on the choice of the $^{13}$C-pocket and on the mass of the pocket when a range of $^{13}$C-pocket strengths is adopted. The GCE model may reproduce within the solar error bars the $s$ contribution to isotopes with $A > 130$. The missing contribution to isotopes in the range between $A = 90$ and 130 found by Travaglio et al. (2004) is confirmed by the present analysis: an additional $s$ process (LEPP-$s$) is required to account for the missing component of 10 $s$-only isotopes ($^{146}$Mo, $^{188}$Ru, $^{192}$Pd, $^{198}$Cd, $^{200}$Sn, $^{208}$Te, and $^{128,130}$Xe). On the basis of the tests made in this paper, the LEPP-$s$ contribution remains essentially the same, independently of the internal structure of the $^{13}$C pocket. The first indications in favor of this process have been analyzed and discussed by Pignatari et al. (2013).

An additional primary contribution is being explored to account for a complementary light $r$ contributions. In spite of promising theoretical improvements related to the explosive phases of massive stars and core collapse supernovae (Arcone & Thielemann 2013 and references therein), as well as recent spectroscopic investigations (Roederer 2012; Hansen et al. 2012, 2013), a full understanding of the origin of the neutron capture elements from Sr up to Xe is still lacking.

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