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Received 2003 May 4, accepted 2003 July 4

Abstract: We discuss possible stellar origins of short-lived radioactive nuclei with mean-life $\tau \leq 100\,\text{Myr}$, which were shown to be alive in the Early Solar System (ESS). We first review current ideas on the production of nuclides having $10 \leq \tau \leq 100\,\text{Myr}$, which presumably derive from the continuous interplay of galactic astrophysics, nucleosynthesis from massive supernovae and free decay in the interstellar medium. The abundance of the shorter lived $^{129}\text{I}$ might be explained by this same scenario. Then we consider the nuclei $^{107}\text{Pd}$, $^{26}\text{Al}$, $^{41}\text{Ca}$ and $^{60}\text{Fe}$, whose early solar system abundances are too high to have originated in this way. Present evidence favours a stellar origin, particularly for $^{107}\text{Pd}$, $^{26}\text{Al}$ and $^{60}\text{Fe}$, rather than an in situ production by energetic solar particles. The idea of an encounter (rather close in time and space) between the forming Sun and a dying star is therefore discussed: this star may or may not have also triggered the solar formation. Recent nucleosynthesis calculations for the yields of the relevant short-lived isotopes and of their stable reference nuclei are discussed. Massive stars evolving to type II supernovae (either leaving a neutron star or a black hole as a remnant) seem incapable of explaining the four most critical ESS radioactivities in their observed abundance ratios. An asymptotic giant branch (AGB) star seems to be a viable source, especially if of relatively low initial mass ($M \lesssim 3M_\odot$) and with low neutron exposure: this model can provide a solution for $^{26}\text{Al}$, $^{41}\text{Ca}$ and $^{107}\text{Pd}$, with important contributions to $^{60}\text{Fe}$, which are inside the present uncertainty range of the $^{60}\text{Fe}$ early solar system abundance. Such a model requires that $^{26}\text{Al}$ is produced substantially on the AGB by cool bottom processing. The remaining inventory of short-lived species in the solar nebula would then be attributed to the continuous galactic processing, with the exception of $^{10}\text{Be}$, which must reflect production by later proton bombardment at a low level during early solar history.

Keywords: solar system: formation — stars: AGB and post-AGB — stars: supernovae: general

Se non è vero è bene trovato

Ancient Italian Motto

1 Introduction

More than forty years ago John Reynolds (1960) at Berkeley announced the discovery of an excess of $^{127}\text{Xe}$ in a meteorite ($^{127}\text{Xe}^*$) and suggested that it could be ascribed to the in situ radioactive decay of $^{129}\text{I}$ ($\tau = 23\,\text{Myr}$). This was proven later, through a demonstration that excesses of $^{127}\text{Xe}$ are directly correlated with stable $^{127}\text{I}$ (Jeffery & Reynolds 1961). These isotopes of iodine are $r$-process products, attributed to supernovae (SNe). It was immediately recognised (Wasserman, Fowler, & Hoyle 1960; see also Cameron 1960) that the observed abundance of $^{127}\text{I}$ could be ascribed to the long term production of $r$-process nuclei in the Galaxy, provided the solar system material had been isolated from the effects of nucleosynthesis events for about $10^8$ years. We can thus recognise how basic questions about the presence of ‘live’ radioactivities in the Early Solar System (hereafter ESS) were associated with supernova (SN) sources since the beginning of modern research on the subject. However, satisfactory answers for the sources of other nuclei have then been looked for in many works and remain an open issue today.

The search for radionuclides other than $^{129}\text{I}$ was, broadly speaking, not successful for a long period of time. Crucial for all subsequent improvements was the fall of the Allende meteorite in 1969. First of all, this event provided more $^{129}\text{Xe}^*$ measurements, and it became possible to sample old materials from the solar nebula including early refractory condensates, the CAIs, or Calcium and Aluminium Inclusions (Podosek & Lewis 1972). These early-formed samples in Allende also yielded quantitative evidence of the existence of radioactive nuclei with a much shorter meanlife. In particular, $^{26}\text{Al}$ ($\tau = 0.79\,\text{Myr}$) was found to have been present in CAIs with a clear correlation of $^{26}\text{Mg}^*$ with $^{26}\text{Al}$ (Lee, Paparanastassiou, & Wasserburg 1976, 1977). Early suggestions by Urey (1955) and Urey & Donn (1956) indicated that the nuclide $^{26}\text{Al}$, which had just then been discovered (Simanton et al. 1954), was the only reasonable source for the heating and melting of planetesimals.

A few years before the fall of the Allende meteorite, the presence of a relatively long-lived species, $^{244}\text{Pu}$...
(\(\tau = 115\) Myr) had been inferred from excesses in neutron-rich Xe isotopes (Rowe & Karoeda 1965). Subsequent work showed Xe to be directly associated with excess fission tracks (Cantelaube, Maurette, & Pellis 1967; Wasserburg, Huneke, & Burnett 1969a, 1969b; Storzer & Pellis 1977) with a Xe isotopic composition showing excesses in \(131, 132, 133, 134, 136\)Xe identical to that resulting from \(244\)Pu spontaneous fission (Alexander et al. 1971). \(244\)Pu-fission Xe was also found in the CAIs from Allende. The hint of excesses of \(142\)Nd found by Lugmair & Marti (1977) pointed to the possible presence of \(244\)Sm (\(\tau = 148\) Myr), a \(\alpha\)-process isotope. Excesses of \(142\)Nd were found to be widespread both in ESS materials and in planetary differentiates and to be well correlated with Sm (Lugmair et al. 1983; Jacobsen & Wasserburg 1984; see also Stewart, Papanastassiou, & Wasserburg 1994). The presence of \(26\)Al (\(\tau = 0.6\) Myr) was established by Kelly & Wasserburg (1978); this nuclide was found to have been present in a large number of iron meteorites representing metal segregation in protoplanets or planetesimals (Chen & Wasserburg 1981a, 1981b; Carlson & Huss 2001).


Recent measurements of \(26\)Al in different H chondrites and a discussion of their use as a fine-scale chronometer can be found in Zinner & Göpel (2000). These workers sought to establish a relationship between the presence of \(107\)Pd (\(\tau = 10\) Myr) and \(26\)Al in CAIs and H4 chondrites and "absolute" ages (measured backward from today) through the \(207\)Pb-\(208\)Pb technique (see also Amelin et al. 2002). As for very fine time resolution, indications have been presented of resolving \(\sim 10^5\) years in the formation of CAIs by \(26\)Al (Hsu, Wasserburg, & Huss 2000).

Table 1 summarises the present status of short-lived radioactivities in the ESS. The first column lists the radioactive nuclide \(R\), the second the stable reference isotope \(S\), the third the meanlife of \(R\) and the fourth the ratio \(N_R/N_S\) for the initial state of the solar system, as estimated from the measurements. The column labeled "Place" refers to the class of objects in which evidence has been found for the presence of \(R\). This means that when

### Table 1. Short-Lived Radioactivities in the ESS

<table>
<thead>
<tr>
<th>(R)</th>
<th>(S)</th>
<th>Mean Life (Myr)</th>
<th>(N_R/N_S_\text{ESS})</th>
<th>Place</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{35})Cl</td>
<td>(^{35})Cl</td>
<td>1.4 × 10^{-6}</td>
<td>2.9</td>
<td>10</td>
<td>CAI</td>
</tr>
<tr>
<td>(^{10})Be</td>
<td>(^{9})Be</td>
<td>2.2</td>
<td>1.6 × 10^{-8}</td>
<td>23</td>
<td>UOC</td>
</tr>
<tr>
<td>(^{53})Mn</td>
<td>(^{55})Mn</td>
<td>5.3</td>
<td>1.4 × 10^{-5}</td>
<td>15</td>
<td>CH</td>
</tr>
<tr>
<td>(^{26})Al</td>
<td>(^{27})Al</td>
<td>1.05</td>
<td>5.0 × 10^{-3}</td>
<td>23</td>
<td>CH</td>
</tr>
<tr>
<td>(^{107})Pd</td>
<td>(^{108})Pd</td>
<td>9.4</td>
<td>2.57</td>
<td>23</td>
<td>CH</td>
</tr>
<tr>
<td>(^{232})Th</td>
<td>(^{233})Th</td>
<td>6.54</td>
<td>1.69</td>
<td>23</td>
<td>CAI</td>
</tr>
</tbody>
</table>

*Place* indicates the type of sample from which the data were derived. CAI refers to Calcium–Aluminum Inclusions; CH refers to phases or assemblages in chondrules but not to those in CAI. PD indicates planetary differentiates (major FeNi-metal segregations or magmatic rocks, e.g. basalts). UOC is used for Unequilibrated Ordinary Chondrites. For \(^{26}\)Al there is evidence of its presence in CH and rarely in PD at abundances far below the ESS value. For \(^{53}\)Mn there is a suggestion in CAIs and, at a somewhat lower level, in PD. For \(^{10}\)Be the first value quoted follows discussion by Lugmair, Shukolyukov, & MacIsaac (1995).

References — (1) McKeegan, Chaussidon, & Robert (2000); (2) Lee et al. (1976, 1977); (3) Srinivasan, Ulyanov, & Goswami 1994; Srinivasan et al. 1996; (4) Birck & Allègre (1985); Rotaru, Birck, & Allègre (1992); Lugmair & Shukolyukov (1998); (5) Shukolyukov & Lugmair (1993a, 1993b); Lugmair et al. (1995); (6) Birck & Lugmair (1988); (7) Tachibana & Hsu (2004a, 2004b); Mostefaoui et al. (2003); (8) Kelly & Wasserburg (1978); (9) Reynolds (1960); Jeffrey & Reynolds (1961); Brazzle et al. (1999); (10) Lugmair & Marti (1977); Lugmair & Galar 1992; (11) Harper & Jacobsen (1994); Lee & Halliday (1995); Yin et al. (2002); Kleene et al. (2002); (12) Rowe & Karoeda (1965); Alexander et al. (1970), Murty, Goswami, & Shukolyukov (1997), (14) McCulloch & Wasserburg (1978); (15) Chen & Wasserburg (1981a, 1981b). 

Estimates for different samples are distributed over two orders of magnitude. However, recent data, derived from Unequilibrated Ordinary Chondrites (UOC), cover a smaller range (one dex).

In the lower panel we include isotopes for which only hints or upper bounds are available.

"Place" refers to very early condensates, like CAIs, then the measurement and the data for the initial state (column 4) coincide. When, instead, measurements refer to younger samples, such as, for example, \(^{107}\)Pd, then the initial abundance should be higher than measured. The initial value depends on estimates for the sample age and on the meanlife of the isotope. From consideration of the observations referred to here, the radionuclides listed in

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formation of some CAIs (up to a few million years) or of auto-metamorphism resulting from the intense $^{26}$Al heat source in small planetesimals (LaTourrette & Wasserburg, 1997). Evidence of $^{26}$Al has been found at intermediate abundance levels in glasses present in chondrules (in unmelted morphosed chondrites) and small excesses of $^{20}$Mg correlated with Al have recently been identified in some eucrites which are basaltic planetary differentiates (Srinivasan et al. 1996). These data appear to make a self-consistent story. We then take the value for $^{26}$Al/$^{27}$Al of $5 \times 10^{-5}$ to represent something like the original inventory of the protosolar nebula and consider the lower values in solar system processed material to represent the passage of time and metamorphism. Some preserved circumstellar grains from stars which existed before the sun show $^{26}$Al/$^{27}$Al ratios several orders of magnitude above the value of $^{26}$Al/$^{27}$Al in the solar nebula.

There are three other cases that require special attention. These are $^{60}$Ca (with a much shorter mean-life, $\tau$, of 0.15 Myr), $^{10}$Be ($\tau = 2.2$ Myr, not produced in stellar sources) and $^{60}$Fe ($\tau = 2.2$ Myr), whose abundance in the ESS is still uncertain (see Table 1). These are discussed in later sections.

In general, the origins of the nuclei in Table 1 are a matter of large debate. They include the continuous synthesis/destilation in the Galaxy by different stellar sources (Schramm & Wasserburg 1970), a local pollution by a nearby star (Cameron & Truran 1977; Wasserburg et al. 1994) and, for certain species, the in situ production in some part of the accretion disk through spallation processes by local cosmic rays or in the X-winds of the forming Sun during its T Tauri stage. These processes were recognised earlier and have recently been intensely investigated (Shu, Shang, & Lee 1996, Shu et al. 1997, 2001). Associated with these works there is also a recent suggestion for production of some species ($^{10}$Be in particular) in cosmic rays (Desch, Srinivasan, & Connolly 2003). Uncertainties in the interpretations are due to the still poorly known intricacies of stellar nucleosynthesis mechanisms (particularly for the $\gamma$-process), of magneto-hydrodynamics in the environments around newly formed stars and of the precursors and formation mechanisms of chondritic materials.

In this paper we present the status of these researches, together with new calculations on short-lived isotope production in AGB stars. A critical issue is the production of $^{60}$Fe and its abundance in the ESS. We first review, in Section 2, the present knowledge of the galactic inventory of short-lived radioactive nuclei, as derived from uniform nucleosynthesis processes through the galactic lifetime and as reflected in the abundance of some of them in the ESS. In Section 3 we broadly consider the alternative ideas on ‘local’ production sites for the short-lived nuclei that cannot be accounted for by the uniform galactic production. In Section 4 the more specific case of a nearby stellar source is illustrated and previous results are updated by discussing recent calculations for massive stars and by presenting our own new set of nucleosynthesis models for
AGB stars of different masses. In this context we show
that a late pollution from a relatively low-mass AGB star
(Wasserburg et al. 1994, 1995) still appears today as a
possible model for explaining the ESS inventory of 26Al,
41Ca, 106Pd and 107Pd.

2 Galactic Inventory of Short-Lived Nuclei

2.1 Uniform Production in the Galaxy as Inflected
from ESS Data

The age of the solar system has been ascertained to
be 4.566 × 10^9 yr (Bahcall, Pinsonneault, & Wasserburg
1995; Allegre et al. 1995). The uncertainty may be less
than 2 Myr (see Tera & Carlson 1999; Amelin et al. 2002).
The most ‘precise’ ages are obtained using the so-called
207Pb–206Pb method. The ages of solar system objects are
determined from the measured abundances of long-
lived parent nuclei today and of their accumulated stable
daughter products in meteorites. This method is applied
to unstable nuclei still preserved now and requires that their
meanlife is sufficiently long. The shortest lived nucleus
to which this rule applies is 251Fm (τ = 1.015 × 10^5 yr).
All nuclei with a meanlife significantly shorter than this
are now effectively extinct, due to exponential decay:
\[ \text{exp}(−2.456 × 10^6 τ/τ). \]
The original presence of shorter lived nuclei can only be inferred from their decay prod-
ucts as the parent isotopes are absent. In many cases,
their ESS concentration was inherited from the abun-
dance established in the interstellar medium as a balance
between stellar production and decay. When this occurs,
one can easily estimate the equilibrium ratio \( N_\text{R}/N_\text{S} \) for
the short-lived radioactive nucleus R with respect to a sta-
ble isotope S produced in the same process. In the simplest
possible galactic model (a closed box, with instantaneous recycling, evolving for a time duration \( T \)) this ratio is
(Schramm & Wasserburg 1970):

\[
\left( \frac{N_R(T)}{N_S(T)} \right)_{\text{UP}} \approx \frac{P_R(p(T)ħ/ℏ)}{P_S(p)p(T)},
\]

where UP means uniform production (in the galaxy),
\( P_R(p) \) is the stellar production rate of the stable nucleus,
expressed as the product of an assumed constant stellar
production factor \( P_R \) and of the average effective produc-
tion rate \( p \) over \( T \), where \( p \) is a function of time, \( P_S \) is the stellar production factor for the radioactive isotope and \( p(T) \) is the effective rate at time \( T \) when production ceased.

If the solar system material is separated from the interstel-
lar medium for a certain time interval \( Δt \), before forming
the first solid condensates (due to the collapse time of the
parent cloud core for example), then the abundance ratio
\( N_{\text{R}}/N_{\text{S}} \) in the oldest meteoritic material will be decreased
with respect to the galactic equilibrium by a factor of
\( \text{exp}(−Δt/τ_R) \). We identify the oldest solar system mate-
rial with CAIs. Any planetary differentiate formed after
a further time delay \( Δt \) will have an abundance ratio further
reduced by \( \text{exp}(−Δt/2τ_R) \). These early abundances can be
established today from the decay products, after a careful
demonstration that their excess is quantitatively correlated
with the chemical properties of the parent element, not
with the daughter element. Descriptions of the procedure
can be found in Lee et al. (1976) and in Wasserburg (1987).
Note that excesses or deficiencies in the abundance of an
isotope may hint at the presence of a radioactive precursor.
However, this may also be due to the widespread intrin-
sic isotopic heterogeneity in the early solar system that is
now well established at the level of a few parts in 10^3. It
is the correlation of excesses of a nuclide with a supposed
parent element in different phases that were formed at the
same time from a homogeneous source that is required to
demonstrate the presence and abundance of a radioactive
parent.

In the above framework, it was argued that 244Pu (an
actinide produced solely by the \( r \)-process and with a
relatively long meanlife) has an ESS abundance approx-
imately compatible with the uniform production in the
Galaxy over a time of around 10^10 yr (Wasserburg,
Busso, & Gallino 1996). A similar compatibility exists
for several purely \( r \)-process nuclei with mean lives larger
than a few Myr, as noted by several authors, among
them Cameron (1993), Cameron, Thielemann, & Cowan
(1993), Cameron et al. (1995) and Meyer & Clayton
(2000). In particular, Wasserburg et al. (1996) noted that
an isolation time \( Δt < 10^7 \) yr would allow one to grossly
explain, through the continuous process of galactic enrich-
ment by the same \( r \)-process type source (assumed to be
a supernova), the ESS abundances of actinides and those
of the shorter lived 125Iff and 146Sm. This assumes that the
\( p \)-nuclei 146Sm are co-produced in \( r \)-process events.
When specific supernova models were considered, such
as that of a 25M⊙ SN by Woosely & Weaver (1995),
though, it turned out that 53Mn, despite its rather short meanlife
(\( τ = 5.3 \) Myr), could also be ascribed to the continuous
injection of supernova material into the ISM (Wasserburg
et al. 1996; Meyer & Clayton 2000). However, as the time
scale of about 10^12 yr is much shorter than the interval of
\( ~10^7 \) yr inferred for 129I, this scenario would overestimate
the abundance of 129I by a large factor. It was therefore
proposed that iodine, together with all \( r \)-nuclei below the
atomic mass number A = 140, be ascribed to a different
supernova type than the one responsible for heavier nuclei.
ESS abundances thus appear to require that the SN explo-
sions contributing iodine must be much rarer events, so
that the solar nebula would be isolated from their contrib-
utions for about 7 × 10^7 yr. This fact, noted much earlier
(Wasserburg et al. 1960; Schramm & Wasserburg 1970;
Cameron et al. 1993, 1997), led to a series of works, both
theoretical and observational, on the ensuing bimodal or
multiple nature of the \( r \)-process source types (for example,
see Wasserburg et al. 1996; Qian, Vogel, & Wasserburg
1998a, 1998b). Further, it has been found that at low
metallicities the observed abundances of heavy \( r \)-process
nuclei in halo stars are very similar to the solar \( r \)-process
pattern (Sneden et al. 1998; Cowan et al. 1999) but that
the light nuclei show significant deficiencies (see Sneden
et al. 2000). It follows that a single, prototypical \( r \)-process
source (which has long been the focus of attention) is no
Although most galactic 26Al certainly comes from massive stars, either from exploding type II SNe (Rauscher et al. 2002; Chieffi & Limongi 2003) or from the winds of Wolf–Rayet stars (Meynet et al. 1997; Arnaud et al. 1997), these stars might not be sufficiently numerous to account for the whole galactic inventory and some contribution might come from AGB stars (Busso, Gallino, & Wasserburg 1999; Mowlavi & Meynet 2000; Nollett, Busso, & Wasserburg 2003) and novae (Starrfield et al. 2000; Iliadis et al. 2002).

Thus, while the sources of heavy r-process nuclei are a matter of active investigation, the usual single source model for all r nuclei is not viable.

2.2 Present Galactic Inventory of 26Al and 60Fe

The process of uniform galactic production discussed in the previous subsection is considerably insufficient to account for the abundance of a few shorter-lived nuclei, including 26Al and 60Fe. The ongoing synthesis of these two isotopes can, in principle, be tested independently through observations, thanks to the fact that their decay is accompanied by the emission of gamma-ray lines (at 1.809 MeV for 26Al and at 1.173 and 1.332 MeV for 60Fe, from the decay of the daughter 46Sc). The 26Al γ-line in the galaxy was first found by Mahoney et al. (1984) using detectors on HEAO (High Energy Astrophysical Observatory). Extensive measurements were made for these nuclei by γ-ray line instruments (for example COMPTEL, the Compton Gamma Ray Observatory, and GRIS, the balloon-borne Gamma Ray Imaging Spectrometer). These observations were reviewed in a number of papers (see Diehl & Timmes 1996; Naya et al. 1998; Prantzos & Diehl 1996 and references therein). Recent results from these experiments, assuming a steady-state production, suggest an average abundance of 26Al in the Galaxy of 3.1 ± 0.9 M⊙ (COMPTEL) and in the range from 2.6 ± 0.4 to 4.5 ± 0.7 M⊙ (GRIS). This distribution of 26Al sources is clumpy, certainly not uniform. The total amount of galactic 26Al corresponds to an average 26Al/27Al in the ISM of a few times 10⁻⁶. This is a factor of 10–25 less than the value in CAIs, indicating that the solar system initially had a much higher enhancement of 26Al (due to the protosolar cloud being closer to the source). Recent models for massive star evolution suggest a value 2.2 ± 0.4 M⊙ as coming from massive star progenitors (Knödlseder 1999). The theoretical and observational estimates are only marginally compatible and a further 1 M⊙ of 26Al from undetected, low-efficiency or dispersed sources cannot be excluded; this might actually improve the agreement (Lentz, Branch, & Baron 1999).

While most of the short-lived nuclei in the ESS listed in Table 1 are certainly a result of stellar nucleosynthesis processes, models of spallation reactions have suggested that the fast particles ejected by the Sun in its T Tauri phase may provide a source for a few species, especially 10Be, 26Fe, 41Ca and 53Mn (Shu et al. 1997; Lee et al. 1997; Naya et al. 1998; Gounelle et al. 2001). In these models the hypothesis was advanced that CAIs and chondrules are also produced in the so-called X-winds from the early Sun. Hence, the high abundance measured in CAIs for 26Al would have to be reconsidered, from its use as a chronometer to its relevance for melting the protoplanetary material (Urey 1955; Fish, Goles, & Anders 1960; Schramm, Tera, & Wasserburg 1970). It has long been known that proton bombardment of bulk solids in the ESS would readily produce 53Mn but greatly underproduce 26Al (Wasserburg & Arnould 1987). The issue at hand for 'local origin' is to seek a self-consistent solution for several short-lived nuclides at the appropriate observed abundances in a physically consistent scenario. In this respect, a model calculation that has attracted a great deal of attention is that by Gounelle et al. (2001) in which the authors were able to predict 10Be, 26Al, 41Ca and much of the 53Mn inferred for CAIs through irradiation of fast particles from the early Sun. The model requires that the irradiation takes place in low-energy impulsive flares in which He is enhanced by several orders of magnitude relative to H in the cosmic rays. The low energy of the cosmic rays and the high abundance of He allows the production of 26Al to be pumped up, which in turn suppresses production of Be. However, the energy spectrum and He
We consider the proposal by Gounelle et al. (2001) to be the requirement for a nearby stellar source contributing to the production of $^{10}\text{Be}$ would be accompanied by $^{26}\text{Al}$ and the ejection of supernova material in jets (Cameron 2001), plausible scenarios only for $^{10}\text{Be}$, which in turn is not produced by stellar nucleosynthesis (for example, planetary differentiates) in which no live $^{26}\text{Al}$ or $^{41}\text{Ca}$ was present (see also MacPherson and Huss 2001) and by Marhas, Goswami, & Davis (2002) provided evidence for the presence of $^{18}\text{Be}$ in meteoritic material in CAIs that is not correlated with $^{26}\text{Al}$ and in much younger material (for example, planetary differentiates) in which no live $^{26}\text{Al}$ or $^{41}\text{Ca}$ was present. The presence of $^{53}\text{Mn}$, evidence for which is clearly found in planetary differentiates, also does not seem to support the X-wind model (Lugmair & Shukolyukov 1998). Also, $^{60}\text{Fe}$ is clearly not produced in this way (Tachibana & Huss 2003a), so that the early X-wind model or local cosmic ray sources (Desch et al. 2003) remain as open and plausible scenarios only for $^{18}\text{Be}$, which in turn is not produced by stellar nucleosynthesis (for example, see Pagel 1997). Similar conclusions as presented here were drawn by several other workers (see Zinner & Göpel 2002). Measurements indicating the absence of $^{26}\text{Al}$ in samples with $^{10}\text{Be}$ seem to rule out the plausibility of recent models of the ejection of supernova material in jets (Cameron 2001), as production of $^{18}\text{Be}$ would be accompanied by $^{26}\text{Al}$ and $^{41}\text{Ca}$ in these models, yielding a correlation between the three nuclides that is not seen. On the other hand, estimates of the absolute age (measured back from the present) of chondrules and CAIs through the Pb-Pb technique (Amelin et al. 2002) yielded age differences consistent with the different $^{26}\text{Al}/^{27}\text{Al}$ values, again supporting the original interpretation of $^{26}\text{Al}$ data as a chronometer of ESS materials. The $^{18}\text{Be}$ data clearly show that the proton bombardment took place in the ESS, but probably this occurred at a level insufficient to coproduce the other short-lived nuclei.

3.2 Is a Close Stellar Encounter Plausible?

The requirement for a nearby stellar source contributing freshly synthesised material to the protosolar cloud seems unavoidable. The possibility of a local contamination by a nearby star was considered by many authors, after the proposal of the supernova trigger advanced by Cameron & Truran (1977). The reader may find more discussion of this model in Podosek & Nichols (1997). To obtain an $^{26}\text{Al}/^{27}\text{Al}$ ratio of $\sim 5 \times 10^{-3}$ in the protosolar cloud would require that about 5% of all the stable $^{26}\text{Al}$ in the ESS be from a close-by SN source, provided that $^{26}\text{Al}/^{27}\text{Al}$ of $\sim 10^{-3}$ is typical of SNe II models (Woosley & Weaver 1995). A consequence would be that a large fraction — over 10% — of the light nuclei (O, Mg and so on) would also come from the same source. The isotopic variations that might be expected from such a contribution have not been observed. One must note that, if the SNe II debris were thoroughly mixed in the protosolar cloud, then there would be no direct observational test as the isotopic ‘anomalies’ would be homogenised; the solar abundances would then not be what we believe or assume them to be — that is, a well mixed average sample of the ISM at the time of the Sun’s formation. The remarkable discovery of a large excess of pure $^{16}\text{O}$ (∼4%) in refractory CAIs (Clayton, Grossman, & Mayeda 1973; Clayton, Mayeda, & Onuma 1976) stimulated much of the search for short-lived nuclei. However, recently these oxygen anomalies have been attributed to mass-independent isotopic effects (Thiemens & Heindenreich 1983) and not related to nuclear processes (Thiemens 1999). This alternative possibility has also been considered by Clayton (2002). A demonstration that the ‘mass independent’ isotopic fractionation can actually be responsible for the effects found in condensed phases has, however, not been made.

An objection to the supernova trigger hypothesis can be advanced on the basis of the increased knowledge of star formation in the Galaxy. There is a clear distinction between the mechanisms controlling the coalescence of isolated cores or globules and those at the base of clustered star formation. Only in the latter case are massive star neighbours present which may play a role in a sequential process of star formation. In the scenario of cluster formation, events of triggering do appear to be present (Kothes, Uyaniker, & Pineault 2001; Pallà & Stahler 2000; Zinnecker 2002), induced by SN ejecta or by massive-star winds from OB associations. The distance from a possible triggering SN to the proto-sun can be roughly estimated assuming spherical symmetry. The mixing ratio needed to obtain the ESS abundances of short-lived species from SN ejecta of the same nuclei would require a distance of a few parsecs (see Cameron et al. 1995). However, further consideration of SN remnant evolution is needed. Recent observational evidence shows that triggering occurs when the shock fronts have slowed velocities down to a few km s$^{-1}$ or less (Perribeh & Zinnecker 1999; Stanke, McCaughrean, & Zinnecker 2002). Such slow motions may require that the expanding SN shells have formed shocks within the ISM through their adiabatic and subsequently ‘snowplow’ phases, travelling a distance perhaps of the order of 50 pc (see, for example, Scheffer & Elsässer 1988, Chapter 6). This is much larger than the value (2.5–10 pc) required by the Cameron et al. (1995) model. A SN trigger like the one originally suggested by Cameron &
Truran (1977) would appear to be a very rare event. Certainly there is a high rate of star formation in OB associations. If, instead, the sun formed alone, or in an isolated binary system as is often the rule for low-mass cloud cores, then a nearby supernova is not expected to be present at all.

The model of AGB contamination also requires a close encounter with an AGB star. This is hard to justify on statistical grounds (Kastner & Myers 1994) and would require the simultaneous occurrence of two phenomena not physically associated (an isolated low-mass cloud-core collapse and a nearby planetary nebula or mass losing AGB star). However, as argued in the previous section, some ESS radioactivities require a close encounter with material from a stellar source of some type. Indications of the nature of such an occurrence and the efficiency with which debris would be trapped in a cloud core can be obtained from theoretical models of stellar nucleosynthesis for different masses and through simulations of the hydrodynamic interactions between a stellar shock and a cloud core (see Vanhala & Boss 2000, 2002, and references therein). This can be done without fully justifying the statistical relevance of such a model. We will follow this approach. In any case, for any model requiring a nearby polluting source, there are a number of unanswered problems.

4 The Nearby Stellar Source: a Reappraisal

In the case of prompt contamination of the local ISM at \( t = 0 \), whatever the source, a result analogous to equation (1) applies. At \( t = \Delta t \), (Wasserburg et al. 1998):

\[
\frac{\alpha_{R,S}^{t=0}}{R_0} = \frac{N_R}{N_0} \Delta t \frac{Q_{R,S}}{Q_0} \times \frac{N_R}{N_0} f_0 \times e^{-\Delta t/\bar{\tau}_R} \tag{2}
\]

where \( \alpha_{R,S}^{t=0} \) is the abundance ratio (radioactive to stable reference nucleus) established in the solar nebula at \( t = \Delta t \). \( Q_{R,S}/Q_0 \) is the enrichment factor of the stable nucleus \( S \) in the stellar wind ejected by the star relative to the ISM. \( N_R/N_0 \) is the abundance ratio (radioactive to stable) in the wind. \( f_0 \) is the mixing ratio for \( t = 0 \) and \( \bar{\tau}_R \) is the lifetime of nucleic R. Note that we use here the net abundances in the envelope of the contaminating source at the time of ejection, which is different from in our previous works. In the earlier works for an AGB source we used the ratio in the He shell and a dilution factor for mixing with the envelope. Here we have calculated the values in the envelope directly. Abundances measured in planetary differentiates that formed later, at \( t = \Delta t \) (as is the case for Pd), can be obtained by applying the further exponential decay factor to the radioactive nuclei of interest. Absolute dating of both ESS samples and of planetary differentiates yield values for \( \Delta t \) of the order of few Myr. This is in accord with other arguments that require a relatively short but significant time delay for protoplanet formation.

It is also possible that values of \( \Delta t \) are slightly different for different samples; this also means that, for example, the time delay to be considered for \(^{103}\text{Pd} \) may be slightly but significantly different from the one related to \(^{56}\text{Fe} \) measurements.

4.1 Short-Lived Nuclei from a 'Local' Supernova

The issues to be discussed here are the questions of which short-lived nuclei in the ESS might have been supplied by a 'local' triggering supernova and whether there are diagnostic characteristics that would identify SN contributions. We will not discuss the \( r \)-process contributions because of the need for diverse \( r \)-sources and also because of the questions relating to SNe II as sources of heavy \( r \)-nuclides as discussed earlier. Our focus will be on the lighter nudes produced by SNe II following available models and recognising that SNe II are known to produce \(^{56}\text{Ni} \). In an earlier report (Wasserburg et al. 1998), following the work of Timmes et al. (1995), we further investigated the problem of whether \(^{26}\text{Al} \), \(^{41}\text{Ca} \), \(^{56}\text{Fe} \) and \(^{53}\text{Mn} \) could be adequately provided by a SN II event, using the models of Woosley & Weaver (1995) as a basis. As recognised by Timmes et al. (1995), the average number ratio of \(^{56}\text{Fe}/^{56}\text{Ni} \) in the SN ejecta of these models is about 8.6, from a wide range of stellar models, the only clear exception being for \( M \simeq 13 M_\odot \). It was found that to match the \(^{26}\text{Al}/^{27}\text{Al} \) ratio of \( \sim 5 \times 10^{-4} \), a mixing ratio of \( \sim 5 \times 10^{-4} \) was required and that this source yielded abundant \(^{41}\text{Ca}/^{40}\text{Ca} \) and \(^{56}\text{Fe}/^{56}\text{Fe} \), of about \( 10^{-5} \). In addition, the inferred relative abundance of \(^{53}\text{Mn} \) implies that \(^{56}\text{Ni}/^{56}\text{Mn} \) is about \( 10^{-3} \). This is far above the observed value shown in Table 1. A SN II model would also require that about 10% of all \(^{16}\text{O} \) in the protosolar cloud, as well as large contributions to other major isotopes, was from the single SN II event. It was proposed that the \(^{26}\text{Al}/^{56}\text{Fe} \) ratio be used as a test of the SN II model.

A new generation of SN II nucleosynthesis models were computed by Rauscher et al. (2002) for a wide range of masses. An up-to-date set of reaction rates (both experimental and theoretical) was used, in conjunction with upgrades in the evolutionary code. These calculations did not include a parametric \( r \)-process model but treated neutron capture reactions during the intermediate and advanced evolutionary stages. As a result, several neutron capture nuclei are produced. In the Rauscher et al. (2002) paper, Tables 8 and 9 (published electronically) give the yields of both radioactive and stable nuclei. Using these results and the published ejected masses, we have calculated the abundances to be found in a protosolar cloud with \(^{26}\text{Al}/^{27}\text{Al} \) of \( 5 \times 10^{-4} \) and \(^{41}\text{Ca}/^{40}\text{Ca} \) of \( 1.5 \times 10^{-4} \). Matching these two values gives the corresponding mixing ratio \( f_0 \) and time interval \( \Delta t \) for initial star masses of \( 15 M_\odot \) (as shown in Table 2, herein) and \( 25 M_\odot \) (see Table 3). It can be seen that most short-lived nuclei are produced abundantly, with the only exception being \(^{103}\text{Pd} \), which is somewhat low. It is clear however that this is not a critical matter. Note that we have not chosen \( \Delta t = 0 \) but found the values of \( f_0 \) and \( \Delta t \) consistent with the assumed \(^{26}\text{Al} \) and \(^{41}\text{Ca} \) values. The principal conclusion is that if \(^{26}\text{Al} \) and \(^{41}\text{Ca} \) are from a SN
In summary, for a SN II source and using $^{26}\text{Al}/^{60}\text{Fe}$ ratios are more similar to those of Woosley & Clayton (2000) to suggest that the source was a peculiar massive star that ejected only the external envelope rich in $^{26}\text{Al}$ and $^{60}\text{Fe}$ and not the innermost region rich in $^{53}\text{Mn}$. This ad hoc model is difficult to evaluate at the present time without further predictions based on the same idea. However, $^{60}\text{Fe}$ is produced in layers external to the innermost regions producing $^{53}\text{Mn}$, increasing the mass cut (to reduce $^{53}\text{Mn}$) would leave, at least, the $^{60}\text{Fe}$ problem unresolved. An important source of concern has been added by Sahijpal & Soni (2003), who showed that all massive star scenarios (SN II, SN Ib/c, non-exploding Wolf-Rayet stars) would provide large contributions of intermediate mass elements to the protosolar cloud. This was discussed earlier by Wasserburg et al. (1998) for SN II sources. All these difficulties should be considered together: while each of them (such as the increased problems in the $^{26}\text{Al}/^{60}\text{Fe}$ ratio deriving from the work of Rauscher et al. 2002) might be individually ascribed to uncertainties in cross sections or model details, we believe that the existence of several correlated reasons of concern (with the abundance of $^{53}\text{Mn}$ being the dominant problem) makes the SN trigger model rather unlikely amongst the available models and data. As indicated above, there is at present no evidence of material from such a supernova, unless of course it was thoroughly mixed. We further note that the overwhelming abundance of presolar grains found in meteorites is from AGB stars and not from SNe II.

### 4.2. Short-Lived Nuclei from an AGB Star

The alternative scenario of an AGB star polluting the Early Solar Nebula was first explored quantitatively by Wasserburg et al. (1994). They concluded that AGB scenarios suitable able to accomplish this task could be found among stellar models with low amounts of neutron captures. This corresponds to the absence or very small concentration of the extra $^{13}\text{C}$ neutron source that is assumed to be present in AGB stars in order to explain the bulk of $x$-process production for average solar system abundances (Gallino, Raiteri, & Busso 1993). This $^{13}\text{C}$ reservoir is known (from observations) to be variable, being different in different classes of AGB stars. This results in a large spread of neutron exposures, corresponding to $10^{2}$ to $10^{6} \text{M}_{\odot}$, which is the source of concern has been added by Sahijpal & Soni (2003), who showed that all massive star scenarios (SN II, SN Ib/c, non-exploding Wolf-Rayet stars) would provide large contributions of intermediate mass elements to the protosolar cloud. This was discussed earlier by Wasserburg et al. (1998) for SN II sources. All these difficulties should be considered together: while each of them (such as the increased problems in the $^{26}\text{Al}/^{60}\text{Fe}$ ratio deriving from the work of Rauscher et al. 2002) might be individually ascribed to uncertainties in cross sections or model details, we believe that the existence of several correlated reasons of concern (with the abundance of $^{53}\text{Mn}$ being the dominant problem) makes the SN trigger model rather unlikely amongst the available models and data. As indicated above, there is at present no evidence of material from such a supernova, unless of course it was thoroughly mixed. We further note that the overwhelming abundance of presolar grains found in meteorites is from AGB stars and not from SNe II.

### Table 2. Short-Lived Nuclei in the ESS from a 15$M_{\odot}$ SN

(Data from Rauscher et al. 2002)

<table>
<thead>
<tr>
<th>Rad.</th>
<th>Ref.</th>
<th>$q_{\delta}$</th>
<th>$(N_{60}/N_{56})_{\delta}$</th>
<th>$(N_{60}/N_{56})_{\delta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26}\text{Al}$</td>
<td>$^{27}\text{Al}$</td>
<td>80.7</td>
<td>5.7 × 10^{-3}</td>
<td>5.0 × 10^{-3}</td>
</tr>
<tr>
<td>$^{41}\text{Ca}$</td>
<td>$^{40}\text{Ca}$</td>
<td>4.7</td>
<td>1.5 × 10^{-2}</td>
<td>1.5 × 10^{-3}</td>
</tr>
<tr>
<td>$^{51}\text{Mn}$</td>
<td>$^{50}\text{Mn}$</td>
<td>95.6</td>
<td>0.15</td>
<td>3.5 × 10^{-3}</td>
</tr>
<tr>
<td>$^{106}\text{Pd}$</td>
<td>$^{106}\text{Pd}$</td>
<td>1.2</td>
<td>3.1 × 10^{-2}</td>
<td>1.3 × 10^{-3}</td>
</tr>
<tr>
<td>$^{60}\text{Fe}$</td>
<td>$^{57}\text{Fe}$</td>
<td>107.8</td>
<td>2.4 × 10^{-3}</td>
<td>4.7 × 10^{-3}</td>
</tr>
</tbody>
</table>

Table 3. Short-Lived Nuclei in the ESS from a 25$M_{\odot}$ SN

(Data from Rauscher et al. 2002)

<table>
<thead>
<tr>
<th>Rad.</th>
<th>Ref.</th>
<th>$q_{\delta}$</th>
<th>$(N_{60}/N_{56})_{\delta}$</th>
<th>$(N_{60}/N_{56})_{\delta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26}\text{Al}$</td>
<td>$^{27}\text{Al}$</td>
<td>3.05</td>
<td>3.3 × 10^{-3}</td>
<td>5.0 × 10^{-3}</td>
</tr>
<tr>
<td>$^{41}\text{Ca}$</td>
<td>$^{40}\text{Ca}$</td>
<td>286.5</td>
<td>1.8 × 10^{-3}</td>
<td>1.5 × 10^{-3}</td>
</tr>
<tr>
<td>$^{51}\text{Mn}$</td>
<td>$^{50}\text{Mn}$</td>
<td>174.5</td>
<td>0.16</td>
<td>3.0 × 10^{-3}</td>
</tr>
<tr>
<td>$^{106}\text{Pd}$</td>
<td>$^{106}\text{Pd}$</td>
<td>2.7</td>
<td>4.7 × 10^{-3}</td>
<td>1.7 × 10^{-3}</td>
</tr>
<tr>
<td>$^{60}\text{Fe}$</td>
<td>$^{57}\text{Fe}$</td>
<td>110.6</td>
<td>1.1 × 10^{-3}</td>
<td>9.0 × 10^{-3}</td>
</tr>
</tbody>
</table>

II source, then the ratio $(^{60}\text{Fe}/^{60}\text{Fe})_{\delta}$ must be very high (in the range 1–5 × 10^{-3}) and $(^{53}\text{Mn}/^{53}\text{Mn})_{w}$ must be extremely high. The new results are essentially consistent with the values calculated from the earlier models, but with some major differences; the extent to which this abundance pattern is diagnostic for SNe II will be discussed below.

The discrepancy in the ESS data is the high value of $(^{53}\text{Mn}/^{53}\text{Mn})_{E}$. Comparison of the values in Tables 2 and 3 with those in Table 1 shows that there is a difference of a factor of 10^{2}. Discussion of $(^{60}\text{Fe})_{\delta}$ is complex, because of the uncertainty in the ratio $(^{60}\text{Fe}/^{60}\text{Fe})_{E}$. However, in both Tables 2 and 3, the value of $(^{60}\text{Fe}/^{60}\text{Fe})_{\delta}$ for a SN II model is high by a factor of 10 with respect to the present upper limit obtained from ESS measurements.

Note that Rauscher et al. (2002) give an average $^{26}\text{Al}/^{60}\text{Fe}$ ratio of approximately 1.5. This is a factor of about 5.7 less than previously found by Woosley & Weaver (1993). This ratio is now in direct conflict with the upper limits set by $\gamma$-ray observations. Note that such a value would considerably increase the importance of $^{60}\text{Fe}$ as a heat source for melting planetesimals in the ESS, compared with previous estimates (Wasserburg et al. 1998; see also Mosser et al. 2003). Recently, new models have been presented by Chieffi & Limongi (2003) in which their $^{26}\text{Al}/^{60}\text{Fe}$ ratios are more similar to those of Woosley & Weaver (1995). In summary, for a SN II source and using the Rauscher et al. (2002) models, we find the following results:

(i) The mixing ratio is roughly compatible with the amount of mass necessary to slow down the ejecta to local velocities ($4 < 10^{12} \text{M}_{\odot}$ of ISM for $\sim 10^{6} \text{M}_{\odot}$ of ejecta). The time scale becomes $\sim 10^{9}$ yr, if one matches the ESS values of $^{26}\text{Al}/^{27}\text{Al}$ and $^{41}\text{Ca}/^{40}\text{Ca}$.
Figure 1  Mixing ratios between the processed envelope material of a solar metallicity AGB star and the ISM from which the solar system formed, for the short-lived nuclei $^{26}$Al, $^{41}$Ca and $^{107}$Pd. The value shown for each isotope is that which is necessary to account for its ESS measurement at $\Delta t = 0$ for each adopted AGB model. In order to obtain a global solution for the three nuclei together, only cases where the mixing ratio derived for $^{107}$Pd, $f_{107}$, is larger than the other two (and hence these must fall in the shaded area below $^{107}$Pd) can be considered, because then radioactive decay can bring the abundances into agreement at a time $\Delta t > 0$. Due to this, only the first two panels (in bold) are acceptable. Note that for 1.5 M$_{\odot}$ models, the large range given for $^{26}$Al is between no cool bottom processes to reasonable contributions from them (Nollett et al. 2003). No cool bottom process was considered in the 3 M$_{\odot}$ models. Hot bottom burning was included in the models for the 5 M$_{\odot}$ star.

The $\alpha$ chain $^{14}$N($\alpha$, $\gamma$)$^{18}$F($\beta^+$+$\nu$)$^{18}$O($\alpha$,$\gamma$)$^{22}$Ne. Thus there is plenty of $^{22}$Ne. The $^{22}$Ne neutron source is only marginally activated in low mass stars ($M \leq 3M_{\odot}$) due to the low temperature in the pulses ($T \leq 3 \times 10^8$ K), but is more significant for higher masses (intermediate mass stars, $3M_{\odot} \leq M \leq 8M_{\odot}$), where the maximum temperature in the bottom of the thermal pulse may reach $3.5 \times 10^8$ K.

A new set of calculations was made for this report using updated cross sections, both considering the neutron flux from a typical $^{13}$C pocket, and excluding it. Calculations were done for stellar models of 1.5, 3 and 5 M$_{\odot}$ at various metallicities. When a $^{13}$C pocket was considered, the standard (ST) choices presented by Gallino et al. (1998) and Busso et al. (2001) were adopted, corresponding to the burning of $4 \times 10^{-6}$ M$_{\odot}$ of $^{13}$C per cycle in low mass stars and of $4 \times 10^{-7}$ M$_{\odot}$ in intermediate mass stars. These cases will be referred to as having ‘high $\Delta t_{13}$’, where $\Delta t_{13}$ is the neutron exposure produced in the $^{13}$C pocket ($\Delta t_{13} = \int N_{n} v_{th} dt$, where $N_{n}$ is the neutron density and $v_{th}$ is the thermal velocity). Models were run through the full evolution of the star and the final values of the abundance ratios for short-lived isotopes in the envelope (such as $^{36}$Ca/$^{40}$Ca) were calculated, taking into account dredge-up, temperature-dependent decay in the various stellar layers and mass loss. The mass loss was parametrised through the Reimers (1975) formula: choices of this free parameter are discussed elsewhere (Gallino et al. 1998; Busso et al. 2001; Abia et al. 2002). The results presented here give essentially the same He shell composition as in Busso et al. (1999), but here we directly estimate envelope abundances at the end of the AGB evolution. This permits straightforward derivation of the mixing ratios for the various nuclei in the ISM.

Our estimated error bars for the ratios in the envelope do not exceed a factor of ~2, with the exception of $^{26}$Al, for which the uncertainty is still large. For this nucleus the range of values given refers to the maximum interval covered by present models. In our calculations, the production of $^{26}$Al computed from the H and He shell is used, with the addition of recent estimates of its synthesis in the envelope, either through hot bottom burning in intermediate mass stars or through cool bottom processes in low mass stars. The range of the ensuing possibilities for the contribution to $^{26}$Al is especially large for low mass stars, spanning the range from pure (limited) production in the H and He shells, to much higher values expected from application of cool bottom process models with high efficiency (Nollett et al. 2003). The range is more restricted for a 3 M$_{\odot}$ star, shown in Figure 1, because no cool bottom processes have been considered. So far, no models of cool bottom processes have been attempted for masses in the 2–3 M$_{\odot}$ range. If analogy to the red giant branch

107Pd has a longer mean life than 26Al (by a factor of 10). In fact, for no time delay \( \Delta t \) (which is not certain), then the efficiency of cool bottom processes for \( \Delta t > 0 \) would allow the other two values to be brought into agreement by assuming free decay for a time interval \( \Delta t \). For \( \Delta t \) of the order of 1 Myr, the result would be to greatly reduce \( ^{41}\text{Ca} \) and even decrease \( ^{26}\text{Al} \), without affecting \( ^{107}\text{Pd} \). On the contrary, any case corresponding to a value \( f_0 \) for \( ^{107}\text{Pd} \) equal to or lower than those deduced from the others at \( t = 0 \) would inevitably fail to yield a solution for any \( \Delta t > 0 \). With these basic rules in mind we see that the only acceptable cases are in the range of low AGB stellar masses with low s-process efficiency, where \( ^{107}\text{Pd} \) provides the required values of \( f_0 \) and then a solution is possible that permits \( \Delta t \geq 0 \). We note instead that the 5.0 \( M_\odot \) model with low neutron exposure requires almost immediate injection of material in order to provide \( ^{41}\text{Ca} \) and would fail to match the \( ^{26}\text{Al} \) data.

We stated that the condition on \( f_0 \) is a necessary one. For it also to be sufficient depends on the possibility of finding a specific solution with reasonable values for \( f_0 \), \( \Delta t \) and \( \Delta \Sigma \) (see eq. (2) and the subsequent discussion). When this is possible, one can further try a direct comparison of the species \( ^{107}\text{Pd} \), \( ^{41}\text{Ca} \) and \( ^{26}\text{Al} \) with the observed abundances of \( ^{99}\text{Tc} \). A self-consistent solution would require a fixed mass for the AGB star and also the same values of \( f_0 \), \( \Delta t \) and \( \Delta \Sigma \) for all four species (although see comment immediately before Section 4.1). The \( ^{40}\text{Fe} \) is especially critical, as it does not depend on the magnitude of the \( ^{12}\text{C} \) pocket which is a free parameter of s-processing in AGB stellar models.

For the 1.5 \( M_\odot \) model, a self-consistent solution is found for \( f_0 \sim 5 \times 10^{-3}, \Delta t \sim 0.8 \) Myr, \( \Delta \Sigma \sim 7 \) Myr. This solution is presented in Table 4. In the second panel of the table we also show the ensuing abundance ratios for a number of short-lived isotopes produced in the AGB model, whose presence and/or quantitative abundance in the ESS still needs a confirmation; we leave these data as predictions, waiting for a test by new measurements. In interpreting the data of Table 4, one has to consider the following:

(i) For \( ^{205}\text{Pb} \), calculations have an intrinsic uncertainty related to the still incomplete knowledge of its electron captures as a function of temperature for the range \( 10^7 \)–\( 1.5 \times 10^8 \) K (see Yokoi, Takahashi, & Arnould 1985; Wasserburg et al. 1994). In view of the choices made in the calculations, the datum of Table 4, column 4, must be seen as an upper limit.

(ii) It is well known that \( ^{99}\text{Tc} \) is produced in AGB stars (Merrill 1952). While no direct evidence for this short-lived nucleus has so far been found in meteorites, there are now new data indicating isotopic effects in Ru (Chen, Papanastassiou, & Wasserburg 2003).

The value in Table 4, when expressed at \( \Delta t = 0 \), corresponds to \( ^{99}\text{Tc}/^{100}\text{Ru} \approx 3.7 \times 10^{-5} \) (a similar value, \( 2.3 \times 10^{-5} \), was found by Wasserburg et al. 1994). This is not very sensitive to the presence of a \( ^{12}\text{C} \) pocket if \( ^{107}\text{Pd} \) is matched, since the abundance ratio between \( ^{99}\text{Tc} \) and \( ^{107}\text{Pd} \) is almost independent of the neutron exposure. The detection of \( ^{99}\text{Tc} \) in meteoritic materials would be very important. However, as noted by Chen et al. (2003), the chemical fractionation (for example, enrichment-depletion) pattern of Tc to be expected in meteoritic materials is completely unknown.

The solution shown in Table 4 would require \( ^{204}\text{Al}/^{207}\text{Al} \approx 2 \times 10^{-2} \) in the envelope, which could be readily reached by cool bottom processing (Nollett et al. 2003). For the 3.0 \( M_\odot \) model, from Figure 1, one would find a discrepancy for \( ^{208}\text{Al} \). In order to obtain a self-consistent solution for this case, we would need to increase the \( ^{26}\text{Al} \) production by a factor of about 3. This shows that good estimates are urgently needed of the efficiency of cool bottom processes for stellar masses above that of the only case (1.5 \( M_\odot \)) so far explored. Calculations of the concurrent effects on \( ^{26}\text{Al} \) synthesis in the range 2–3 \( M_\odot \) should clarify whether or not this nucleus can be provided in sufficient amounts. We conclude that acceptable

Table 4. Short-lived Nuclei from a Low Mass Star with Cool Bottom Processes

<table>
<thead>
<tr>
<th>Rad.</th>
<th>Ref.</th>
<th>( f_0 )</th>
<th>( N_0/N_0\Delta t )</th>
<th>( N_0/N_0\Delta \Sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{26}\text{Al} )</td>
<td>( ^{40}\text{Ca} )</td>
<td>0.99</td>
<td>( 4.7 \times 10^{-4} )</td>
<td>0</td>
</tr>
<tr>
<td>( ^{99}\text{Tc} )</td>
<td>( ^{26}\text{Al} )</td>
<td>0.99</td>
<td>( 9.3 \times 10^{-5} )</td>
<td>1.4 \times 10^{-4}</td>
</tr>
<tr>
<td>( ^{41}\text{Ca} )</td>
<td>( ^{41}\text{Ca} )</td>
<td>1.01</td>
<td>( 9.8 \times 10^{-3} )</td>
<td>( 4.5 \times 10^{-5} )</td>
</tr>
<tr>
<td>( ^{26}\text{Al} )</td>
<td>( ^{41}\text{Ca} )</td>
<td>0.99</td>
<td>( 2.7 \times 10^{-3} )</td>
<td>( 2.4 \times 10^{-6} )</td>
</tr>
<tr>
<td>( ^{99}\text{Tc} )</td>
<td>( ^{41}\text{Ca} )</td>
<td>1.01</td>
<td>( 1.1 \times 10^{-2} )</td>
<td>( 4.0 \times 10^{-5} )</td>
</tr>
<tr>
<td>( ^{36}\text{Cl} )</td>
<td>( ^{36}\text{Cl} )</td>
<td>1.02</td>
<td>( 7.1 \times 10^{-3} )</td>
<td>( 3.2 \times 10^{-6} )</td>
</tr>
<tr>
<td>( ^{93}\text{Zr} )</td>
<td>( ^{92}\text{Zr} )</td>
<td>1.01</td>
<td>( 2.3 \times 10^{-2} )</td>
<td>( 1.1 \times 10^{-4} )</td>
</tr>
<tr>
<td>( ^{107}\text{Pd} )</td>
<td>( ^{107}\text{Pd} )</td>
<td>0.99</td>
<td>( 2.3 \times 10^{-2} )</td>
<td>( 2.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>( ^{205}\text{Pb} )</td>
<td>( ^{205}\text{Pb} )</td>
<td>1.07</td>
<td>( 1.3 \times 10^{-1} )</td>
<td>( 6.6 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

(*) Estimate including cool bottom processes from Nollett et al. (2003).
scenarios might have AGB sources in the mass range 1.5 M_☉ ≤ M ≤ 3 M_☉. These solutions do not extend to 82Hf, despite the fact that this nucleus receives small contributions from the s-process. As noted in previous works, the AGB production is in this case grossly insufficient. Issues regarding 82Hf are as described in Wasserburg et al. (1996b); its ESS inventory must be ascribed to the long term production of the heaviest s-process nuclei (with a lower cutoff at Ba, see Qian et al. 1998a).

4.3 The 60Fe Problem

Concerning the more difficult case of 60Fe, it was recalled in the previous section that for SNe II 60Fe is produced at exceedingly high abundances compared with 26Al. We now consider the question of whether it might be produced in suitable amounts in AGB stars. Our previous investigation (Wasserburg et al. 1994) showed that significant 60Fe production takes place in the He shell of AGB stars. The physics of AGB stars appears to be rather well defined (see Busso et al. 1999). The nuclear reaction rates involved are provided by extensive and sophisticated laboratory studies at the appropriate energies (Bao et al. 2000). As a result, the model of an AGB source for short-lived nuclei in the ESS has very strict constraints. As the envelope of an AGB star is well mixed, its composition is fixed by the initial conditions (mass and metallicity) and the three dynamical variables: the degree of neutron exposure in the radiative zone (that is, the 13C pocket), the mass loss and the degree of cool bottom processing. The list of nuclei that can be made and those that cannot be made (such as 26Al, 32S, 33S and 35Cl) is explicit both qualitatively and quantitatively; in particular, the nuclide 60Fe is a required product of AGB stars. In general, the main uncertainty lies in the role used for determining mass loss.

Synthesis of 60Fe requires two neutron captures, first on stable 58Fe and then on unstable 59Fe (τ ≈ 65.4 days). Operation of the reaction branching here, through the neutron-rich channel feeding 60Fe, needs rather high neutron densities. These densities can be achieved only by the 22Ne neutron source in the pulses, where the temperature is high enough. Hence, virtually no 60Fe production occurs in the low-neutron density 13C-burning phase. Wasserburg et al. (1994) found a local ratio in the production zone for 60Fe/56Fe of 10^{-4} to 10^{-3}. This provided full compatibility of an AGB source with estimates of the ESS inventory then available. Updated computations for a 1.5 M_☉ star of solar metallicity (Busso et al. 1999) subsequently gave a 60Fe/56Fe ratio of 1.9 × 10^{-4} for the He shell. We present here the more extended results of the models mentioned above, in which we have determined the evolution of the 60Fe/56Fe ratio in the envelope pulse after pulse. These ratios do not depend on the uncertain choices for the 13C pocket formed in the radiative interpulse phases, as 60Fe is entirely produced in the convective pulses.

The extent to which an AGB source could quantitatively provide sufficient 60Fe for the ESS is at present a problem and may be the key to understanding the nature of the contaminating stellar source. A major uncertainty in the 60Fe production lies in the neutron capture cross sections of both 59Fe and 60Fe which are based on theoretical estimates only. The Maxwellian-averaged cross section of 60Fe at 30 keV is rather low: ⟨σ⟩(30 keV)(60Fe) = 3.65 mbarn, according to Woosley et al. (1978). Consequently, only a small production of the 60Fe produced can undergo further neutron captures. On the other hand, 59Fe synthesis directly depends on the neutron densities. These densities can be achieved only by the 59Fe, whose value at 30 keV, as estimated by Wasserburg et al. (1978), is 12.3 mbarn. More recent calculations, based on a different theoretical approach, have been performed by Rauscher & Thielemann (2000) who obtain ⟨σ⟩(30 keV)(59Fe) = 22.5 mbarn. We adopt estimates here from Wasserburg et al. (1978), but we verified that, by using instead the Rauscher & Thielemann (2000) cross sections for both 59Fe and 60Fe, our production of 60Fe (Table 5) would be increased by factors of about 1.8 for all the 1.5 M_☉ and 3 M_☉ models and about 2.5 for the 5 M_☉ models. We may conclude that our predictions cannot change, due to variations in the neutron capture cross sections, by more than a factor of two. With this limit in mind, we have calculated the mixing factor f_0 necessary to achieve a given value of (N_{60Fe}/N_{56Fe}) for the case of M_☉ = 0 for three stellar masses of 1.5, 3.0 and 5 M_☉, each for three different metallicities (Z = 0.02, 0.01, and 0.006). The resulting mixing factors are shown in Figure 2 and the corresponding envelope abundances for 60Fe and 59Fe are shown in Table 5. It can be seen that for M = 1.5 M_☉ and Z = 0.02, a value of f_0 = 10^{-5} is obtained for (N_{60Fe}/N_{56Fe}) of 3 × 10^{-5}. To achieve the higher value of 10^{-6} for (N_{60Fe}/N_{56Fe}) for (N_{60Fe}/N_{56Fe}) (Mosterfaun et al. 2003) for this stellar mass, a high value of f_0 (∼ 0.1) would be required. For the case of a 3 M_☉ star, values for (N_{60Fe}/N_{56Fe}) of 3 × 10^{-7} are readily achieved for f_0 ≤ 10^{-5} at Z = 0.02 and higher (N_{60Fe}/N_{56Fe}) values can be obtained for Z = 0.006. The 5 M_☉ star can readily produce (N_{60Fe}/N_{56Fe}) values up to 10^{-8} for f_0 < 10^{-5}. If we require the AGB source to have close to solar Z, then the value of (N_{60Fe}/N_{56Fe}) must be ≤ 3 × 10^{-5} for a 3 M_☉ star and ≤ 1 × 10^{-3} for a 1.5 M_☉ star. (We note that the global solution for the

<table>
<thead>
<tr>
<th>Mass</th>
<th>Metallicity</th>
<th>(N_{60Fe}/N_{56Fe})</th>
<th>f_0</th>
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</thead>
<tbody>
<tr>
<td>1.5 M_☉</td>
<td>0.006</td>
<td>5.4 × 10^{-5}</td>
<td>0.29</td>
</tr>
<tr>
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<td>0.19</td>
<td>3.7 × 10^{-5}</td>
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<td>0.02</td>
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</tr>
<tr>
<td>3.0 M_☉</td>
<td>0.006</td>
<td>1.6 × 10^{-3}</td>
<td>0.29</td>
</tr>
<tr>
<td>0.01</td>
<td>5.9 × 10^{-5}</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>3.4 × 10^{-5}</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>5.0 M_☉</td>
<td>0.006</td>
<td>4.5 × 10^{-3}</td>
<td>0.29</td>
</tr>
<tr>
<td>0.01</td>
<td>4.0 × 10^{-3}</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>3.1 × 10^{-3}</td>
<td>0.94</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Abundance Ratios 60Fe/56Fe and Overabundance χ_{60} in the Stellar wind (w), at the End of the AGB Evolution for the Models Shown in Figure 2.
The initial abundance then is critically dependent on mixing ratios after protoplanets formed (less, there was some indication that $^{60}$Fe was present and local ISM needed to account for an ESS $^{60}$Fe/$^{56}$Fe ratio in the bottom three lines (long dash) are for the 1.5 $M_\odot$ case for different values of $Z$. The middle three lines (short dash) are for 3 $M_\odot$ and the unbroken top three lines are for 5 $M_\odot$.

1.5 $M_\odot$ model, including $^{26}$Al, $^{44}$Ca and $^{107}$Pd, yields the lower value of ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ $\approx 3 \times 10^{-8}$, see Table 4.) In general, considering the results for $^{60}$Fe and the range of possible solutions for the other nuclei, it appears that an AGB source with 1.5 $M_\odot \leq M \leq 3 M_\odot$ still offers plausible possibilities for explaining $^{60}$Fe together with $^{26}$Al, $^{44}$Ca and $^{107}$Pd.

Evidence for the presence of $^{60}$Fe was first seen by Birck & Lugmair (1988) who found variations in the abundances of Ni isotopes in CAIs from Allende with an excess of $^{60}$Ni. However, these effects were not correlated with Fe/Ni. If these variations were attributed to $^{60}$Fe, then this would correspond to ($^{60}$Ni/$^{59}$Ni)$_{UOC}$ $\approx 1.5 \pm 0.5 \times 10^{-8}$. However, it has been well known that there are general isotopic anomalies (variability in isotopic composition) both in CAIs and other ESS material. These effects are not obviously attributable to short-lived nuclei. The demonstration of isotopic shifts in the daughter nuclide must be correlated with the parent element abundance as discussed above.

Evidence for the presence of $^{60}$Fe was found in the planetary differentiates Chervony Kvit, Jevinas and Caldera (Shukolyukov & Lugmair, 1993a, 1993b, 1996). However, no clear correlation was found for $^{60}$Ni excesses with Fe in these samples and the data are widely scattered. Nonetheless, there was some indication that $^{60}$Fe was present after protoplanets formed ($\Delta_{\gamma} \geq 0$, see ref. 5 in Table 1). The initial abundance then is critically dependent on the values of ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ as inferred from the data ($3.9 \times 10^{-8}$ to $4.3 \times 10^{-8}$) and an estimate for the time scale $\Delta_{\gamma}$. The most recent efforts dedicated to the search for $^{60}$Fe occurred in studies of unquenched ordinary chondrites by measuring Ni deficient FeS phases. The critical reports are by Tachibana and Huss (2003a, 2003b) who found ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ ratios of $(1.08 \pm 0.23) \times 10^{-7}$ and $(1.73 \pm 0.53) \times 10^{-7}$ and by Mostefaei et al. (2003) who found ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ $= 7.5 \times 10^{-5}$. Both groups sought to establish correlations of $^{60}$Ni/$^{56}$Ni with $^{56}$Fe/$^{56}$Ni. The evidence in the above three reports appears quite convincing for the presence of $^{60}$Fe at a rather high abundance. If we ignore the question of ‘formation interval’ ($\Delta_{\gamma, UOC}$), then one set of results points to a value of $\sim 10^{-7}$ and the other to $\sim 10^{-6}$. The latter value then appears to indicate that the early estimate by Birck & Lugmair (1988) from just the $^{60}$Ni anomaly in CAIs was approximately correct. The difference between the two values is so large as to make a firm conclusion about the AGB model very difficult. If the true value of ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ is approximately $10^{-7}$, then a SN source would be excluded, not only according to Rauscher et al. (2002) models, but also by adopting previous nucleosynthesis predictions by Woosley & Weaver (1995).

For ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ of approximately $(1-3) \times 10^{-7}$ and $\epsilon_{u}$ of about $(0.5-1) \times 10^{-7}$, it is then required that the contaminating source be an AGB star less massive than 3.0 $M_\odot$, if $Z \approx 0.02$. Obtaining values of ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ of $\sim 10^{-6}$ would require an AGB source of $M \simeq 3 M_\odot$ and/or $Z$ well below $Z_C$. We note that for $M > 3 M_\odot$, there would be a serious conflict matching $^{60}$Fe/$^{56}$Fe with the $^{26}$Al/$^{27}$Al, $^{44}$Ca/$^{40}$Ca and $^{107}$Pd/$^{106}$Pd results. An AGB star with $M$ of 2-3 $M_\odot$ still appears to be the most promising possibility, although, as we have mentioned, present models (which do not include cool bottom processes) would suffer from a shortage of $^{26}$Al by a factor of about 3. If cool bottom processes could operate in this mass range, then $^{60}$Fe at levels of ($^{60}$Fe/$^{56}$Fe)$_{UOC}$ $\approx 3 \times 10^{-7}$ might be explained together with $^{107}$Pd and $^{26}$Al in this source.

As noted earlier by Wasserburg et al. (1998), for high $^{60}$Fe/$^{56}$Fe values there should be large isotopic shifts in FeS materials with modest Fe/Ni fractionation. Most recent data have focused on very great enrichments of Fe relative to Ni in FeS using ion probe techniques at low precision. However, a more definitive test could be done on mineral phases in equilibrium formed from a melt. The first efforts by Shukolyukov & Lugmair (1993) sought effects in enstatites that are Ni-deficient due to the apparent separation of an Fe–Ni core on their parent planet. However, it is possible that liquid droplets such as unmetamorphosed chondrules would show sufficient fractionation between Fe and Ni (for example, between olivines and pyroxenes and metal) so that high precision (0.5 $\epsilon_{u}$, where 1 $\epsilon_{u}$ = 1 part per ten thousand) Thermal Ionisation Mass Spectrometry (TIMS), or Ion Coupled Plasma Mass Spectrometry (ICPMS) methods could be used to establish isochrons. This would permit measurements on phases with very different paragenesis than FeS and FeO samples. An enrichment factor of 7.5 would yield a $\epsilon_{u}$ effect at $^{60}$Fe/$^{56}$Fe $\approx 10^{-6}$. Internal $^{60}$Fe-$^{56}$Ni isochrons in such samples would greatly clarify the matter.
5 Conclusions
In this paper we have reviewed the studies on the origin of ESS short-lived radioactivities, after a brief account of the relevant measurements and of the hypotheses previously presented for their interpretation. It now appears that all nuclei with meanlife in excess of 10 Myr can be explained by the continuous injection of supernova debris into the ISM, where a quasi-steady state between production and decay could be established. This assumes that two (or more) r-process sources are dominantly producing the heavy r-nuclei. In addition, $^{107}$Pd (mean life 5.3 Myr) can also be produced by long-term galactic nucleosynthesis. Other nuclei with a short mean life, from $^{102}$Pd ($\tau = 9.4$ Myr) down to $^{26}$Ca ($\tau = 0.15$ Myr), all require a late contamination by a stellar source, with the exception of $^{40}$Fe. Presently available chemical yields from massive star evolution and explosion indicate that a nearby supernova source does not appear capable of accounting for the ESS concentration of $^{26}$Al, $^{41}$Ca and $^{107}$Pd, with-out exceeedingly overproducing $^{58}$Ni and probably also $^{60}$Fe. A much better situation is provided by nucleosynthesis models for low mass AGB stars undergoing marginal $r$-processing and cool bottom processing, as might be the case for stars below 3 $M_{\odot}$. A contamination by such a source naturally accounts for the measured ESS concentrations of the three isotopes above and also gives estimates for $^{40}$Fe within the present experimental uncertainty, for reasonable choices of the ages of meteoritic samples in which measurements of short-lived nuclei are available.

The critical issue for $^{56}$Ni is the extent to which cool bottom processes can be effective in stars of masses between 2.0 $M_{\odot}$ and 3.0 $M_{\odot}$. This issue is not yet resolved.

As a concluding remark we want to stress that in some cases the abundances of short-lived nuclei in different samples of early solar system material are not related in a simple self-consistent pattern. This applies, for example, to $^{102}$Pd or to $^{107}$Pd abundances in different samples and can be seen in numerous examples where isochrons of good quality are obtained but the results are not in accord with the usually inferred "times of formation". Some samples with ‘primitive’ abundances appear to be younger by large amounts (\$\Delta t \sim 16$ Myr) and, alternatively, there are planetary differentiates that are thought to be 'younger' but have unusually high abundances of, say, $^{107}$Pd (see also Hutcheon et al. 1992, 1998; Lugmair & Sikolyukov 1998; Chen & Wasserburg 1996). In parallel with improved efforts for modeling the production of short-lived nuclei in stars and locally, also more intense and careful experimental attempts are needed, comparing the abundances of different short-lived nuclei in the same objects and pursuing a better insight into the possible mechanisms of resetting.

Acknowledgments
We all wish to thank John Lattanzio for his generous share of information, data, advice and good wines. Suggestions of critical importance and stimulating comments were provided by G. Lugmair, E. Zinner, J. José, O. Straniero, M. Limongi and A. Chieffi. In particular, we would like to acknowledge the extremely helpful and detailed comments and criticisms by G. Huss that greatly aided in improving this report. Cynthia A. Craig reminded us of Italian aphorisms, which are useful in a wide variety of occasions. M.B. and R.G. acknowledge support from the Italian MIUR-FIRB Project M2. 'Astrophysical Origin of Heavy Elements beyond Fe'. G.J.W. acknowledges support from NASA NAGS-11725. Caltech Division Contribution 8905(1107).

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