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INJECTION OF FRESHLY SYNTHESIZED ^{41}Ca IN THE EARLY SOLAR NEBULA BY AN ASYMPTOTIC GIANT BRANCH STAR

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ABSTRACT

We show that ejecta from the envelope of one asymptotic giant branch star of $M \sim 3\ M_{\odot}$ may account for many of the short-lived nuclei in the early solar system and also for the recent evidence of the presence of ^{41}Ca ($\bar{\tau}_{41} = 1.50 \times 10^5$ yr) in early solar nebular condensates. This would require that the injection into the protosolar molecular cloud took place within a narrow time interval of (5–7) $\times 10^5$ yr before the formation of the solar system. If true, this places extremely tight constraints on the whole process of injection mixing and collapse. The timescales for both ^{41}Ca and ^{26}Al require that the placental medium be a dense molecular cloud (2×10^3–8×10^3 H cm^{-3}). If the observed residual ^{41}Ca is instead produced by a proton bombardment mechanism within the early solar system, similar to what appears necessary to explain ^{53}Mn, then the time interval is relaxed but would still be (1–2) $\times 10^6$ yr from consideration of ^{26}Al.

Subject headings: ISM: abundances — nuclear reactions, nucleosynthesis, abundances — solar system: formation — stars: AGB and post-AGB

1. INTRODUCTION

We present the yield of ^{41}Ca produced in asymptotic giant branch (AGB) stars that may be the source of some short-lived nuclei present in the solar nebula. Strong evidence has recently been presented by Srinivasan, Ulyanov, & Goswami (1994, hereafter SUG) for the presence of ^{41}Ca in the early solar system. The mean life of ^{41}Ca is $\bar{\tau}_{41} = (1.50 \pm 0.08) \times 10^5$ yr (Mabuchi et al. 1974; Paul, Ahmad, & Kutschera 1991; Klein et al. 1991). All short-lived radioactive nuclei that have been clearly identified as having been present in early solar system material are listed in Table 1. Of these nuclei (excluding ^{41}Ca), ^{26}Al has the shortest lifetime and has been found to have been present in materials called CAIs (calcium-aluminum–rich inclusions) that are enhanced in the refractory elements Al, Ca, Ti, and Mg (Lee, Papanastassiou, & Wasserburg 1977). We note that ^{26}Al is also abundant in the Galaxy as determined by γ-ray line observations (Mahoney et al. 1984; Diehl et al. 1994). The CAIs have bulk compositions resembling high-temperature condensates of solar matter. They have been interpreted as the product of melting of aggregates of early condensates formed in a locally heated part of the solar nebula. These liquids subsequently crystallized upon cooling and then partly reacted with volatiles at low temperatures. Evidence of ^{53}Mn is sometimes found in some CAIs (see Birck & Allègre 1988). Clear evidence of ^{129}I is also found associated with late-stage volatile alteration of the older refractory materials. Short-lived ^{26}Al has been used as the key chronometer for assessing the timescale between its production in stellar sources and the collapse of the protosolar nebula, which from consideration of free-fall dynamics ($\tau_{\rm ff} \approx 4 \times 10^7/\sqrt{n_{\rm H}}$ yr) implies an initial density ($n_{\rm H}$) in the placental cloud of $\sim 2 \times 10^3$ H cm^{-3}.

In the report by SUG, a good correlation of ^{41}K* with ^{40}Ca was found in the analyzed CAIs, taking spectral interferences at mass 41 due to ^{40}Ca^{42}Ca^{++} into careful account (Hutcheon, Armstrong, & Wasserburg 1984; Wasserburg 1985). SUG interpreted their results as due to the in situ decay of ^{41}Ca with an abundance ratio of ^{41}Ca/^{40}Ca $= (1.5 \pm 0.3) \times 10^{-8}$. They also showed that ^{26}Al was present in the same CAIs, with an abundance ratio of ^{26}Al/^{27}Al $= 5 \times 10^{-5}$, in agreement with earlier observations.

The usual rule has been that the timescale between production of radioactive species in stellar sources and the formation of the solar system is fixed by the shortest lived nucleus that was present alive in the early solar system. However, as the abundance level gets very low, consideration must be given to cosmic-ray and local irradiation sources. The most reasonable mechanism for ^{41}Ca production is from n-capture on ^{40}Ca. Clear evidence of low-energy n-captures due to cosmic-ray interactions in the solar system has been found in both meteorites and lunar rocks (Eugster et al. 1970; Russ et al. 1971; Curtis & Wasserburg 1975). However, the value ^{41}Ca/^{40}Ca $\sim 10^{-8}$ is about a factor of 10 to 100 greater than expected from neutron captures on ^{40}Ca as argued by SUG.

The broad panoply of short-lived nuclei that have been found in the early solar system has been attributed to a variety of nuclear astrophysical processes and sites. From considerations of stellar and nuclear processes, Cameron (1993) has outlined general sources and abundances of these nuclei so far discovered or hinted at. A fully self-consistent model should contain the abundances of a large set of those nuclei from different zones of a limited number of stars as well as the extent of dilution of stellar ejecta with the ambient interstellar medium (ISM). Following the extensive work of s-process nucleosynthesis in AGB stars suffering thermal pulses (TP-AGB) by Gallino Raiteri, & Busso (1993), the case of one AGB star contaminating the ISM with short-lived nuclei from the terminal stages has been studied by Wasserburg et al. (1994, hereafter WBGR). Their approach was to calculate the net number of nuclei ejected from typical AGB stars of different masses with the only free parameter being the mean neutron exposure. In their calculations the neutron source is parameterized by the amount of ^{13}C injected in each thermal instability. The calculations were then carried out with a

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TABLE 1

Mean Lives of Short-lived Nuclei Identified in the Early Solar System

Nuclide	Mean Life (yr)	Production Site	AGB Possible Source
^{26}Al........	1.1×10^6	H-Burning ^{25}Mg$(p, \gamma)^{26}$Al	+
^{41}Ca	1.5×10^5	^{40}Ca$(n, \gamma)^{41}$Ca	+
^{53}Mn	5.3×10^6	?, Charged particle reactions	−
^{60}Fe	2.2×10^6	*s*-branched, *r*	+
^{107}Pd	9.4×10^6	*s*-main chain, *r*	+
^{129}I	2.3×10^7	*r*	−
^{146}Sm......	1.49×10^8	*p* or (γ, n)	−
^{244}Pu	1.18×10^8	*r*	−

self-consistent stellar evolution model. The contributions from both the He and H zones to the envelope were included. Using the observed ^{107}Pd/^{108}Pd ratio in planetary differentiates, one obtains a relationship between the mean neutron exposure (τ_0) and the dilution factor, $M_{\rm He}/M_{\rm SC}$, of the mass of He zone matter ($M_{\rm He}$) mixed into the AGB envelope and ejected by stellar winds into the mass of the protosolar cloud ($M_{\rm SC}$). It was found that the observations on ^{107}Pd and ^{60}Fe could be explained (1) by a dilution factor of $M_{\rm He}/M_{\rm SC} \approx 1.5 \times 10^{-4}$, (2) for $\tau_0 \sim 0.03$ mbarn^{-1}, and (3) for a time interval between injection and formation of early nebular condensates of at most $\sim 2 \times 10^6$ yr (see Table 8, third column, in WBGR and Table 2 in this paper). The abundances of ^{60}Fe recently discovered by Shukolyukov & Lugmair (1993) are in agreement with the calculations if the timescale for early planet formation and differentiation is less than 5×10^6 yr. This constraint is supported by new experimental results by Lugmair, Shukolyukov, & MacIsaac (1994a, b). The ^{26}Al, which is produced in the H-burning zone (see Forestini, Paulus, & Arnould 1991), is also produced in the correct proportion, taking into account the H-burning material that is subject to neutron exposure (WBGR). Predictions were then made in this model for the abundances of all short-lived nuclei with $\bar{\tau} > 10^6$ yr.

2. RESULTS

After the report by SUG, we inspected the calculated abundances of ^{41}Ca in AGB stars as determined in our original calculations (WBGR). The nuclide ^{40}Ca is bypassed in the main *s*-process path, but any ^{40}Ca originally present will be exposed to a neutron fluence, thus producing ^{41}Ca. The ^{41}Ca mean life under the appropriate stellar conditions (Cosner & Truran 1981) are orders of magnitude longer than the duration of the neutron irradiation.

The experimental 30 keV Maxwellian-averaged cross section for ^{40}Ca is $\sigma_{40} = (6.7 \pm 0.7)$ mbarn (Musgrove et al. 1976). Thus, for a neutron exposure $\tau_0 = 0.03$ mbarn^{-1}, there is little depletion in the ^{40}Ca abundance by neutron captures. Even for the much higher mean neutron exposure, $\tau_0 = 0.28$ mbarn^{-1}, ^{40}Ca is depleted by only a factor of 2 in the He shell. The rate of destruction of ^{41}Ca by neutron captures is about 100 times faster than that of ^{40}Ca. It occurs through three different neutron channels: (n, γ) to ^{42}Ca, (n, p) to ^{41}K and (n, α) to ^{38}Ar. As noticed by Clayton (1982), the most important one is the (n, α) channel, amounting to about 90% of the total *n*-cross section. Note that the theoretical estimate by Woosley et al. (1978) is a factor of 2 lower than the recent experimental determination by Wagemans, Druyts, & Barthélémy (1994). Since the cross section for destruction of ^{41}Ca is very much larger than that of ^{40}Ca, for all neutron exposures the ^{41}Ca produced in the He shell relative to the ^{40}Ca remaining is given to a good approximation by $^{41}{\rm Ca}/^{40}{\rm Ca} \approx \langle\sigma_{40}\rangle/\langle\sigma_{41}\rangle$. According to Wagemans et al. (1994), there is an important temperature dependence of the ^{41}Ca cross section different from the usual $1/v$ law. However, due to the very high total *n*-capture cross section on ^{41}Ca, the net effect on its production is dominated by the last small neutron exposure during the marginal activation of the ^{22}Ne source, at a temperature of 26 keV (see WBGR). We estimate the range in ^{41}Ca/^{40}Ca to be $(1.0 \pm 0.2) \times 10^{-2}$ considering the values obtained by us for $\tau_0 = 0.03$ and 0.28 mbarn^{-1}. A statement of this ratio was previously given by Cameron (1993) in a good estimation.

The ^{41}Ca/^{40}Ca isotopic production ratios were calculated over a series of thermal pulses in the He shell, by the effect of both the ^{13}C and the ^{22}Ne neutron sources and by taking into account the interpulse decay. The production ratio of ^{41}Ca/^{40}Ca is essentially independent of stellar mass. However, the time between pulses changes and can be shown to depend on the core mass reached by the star during a given thermal pulse. For stars of about 3 $M_\odot$, the time between pulses in the most advanced phases is $\sim 4 \times 10^4$ yr (Boothroyd & Sackmann

TABLE 2

Calculated Abundances of Identified Short-lived Nuclei for 3 $M_\odot$ AGB Star

Isotope Ratio	$N^R_{\rm He}/N^I_{\rm He}$	$q^I_{\rm He}/q^I_{\rm SC}$	$\alpha_{R,I}(0)$	$\alpha_{R,I}$(0.5, Myr)	$\alpha_{R,I}$(5.0 Myr)
^{41}Ca/^{40}Ca	1.0×10^{-2}	1.0	3.0×10^{-7} $(f = 0.2)$ 1.5×10^{-6} $(f = 1.0)$	1.1×10^{-8} 5.4×10^{-8} $\{1.50 \times 10^{-8}\}_{\rm CAI}$	
^{107}Pd/^{108}Pd......	0.184	1.28	3.4×10^{-5}	3.2×10^{-5}	2.0×10^{-5} $\{2.0 \times 10^{-5}\}_{\rm PL}$
^{60}Fe/^{56}Fe.........	1.0×10^{-4}	0.85	1.2×10^{-8}	9.8×10^{-9}	1.3×10^{-9} $\{4 \times 10^{-9}\}_{\rm PL}$
^{26}Al/^{27}Al	0.8	1.0	0.9×10^{-4} [a] 2.5×10^{-4} [b]	5×10^{-5} 15×10^{-5} $\{5 \times 10^{-5}\}_{\rm CAI}$	0.7×10^{-6} 2×10^{-6}

Note.—$M_{\rm He}/M_{\rm SC} = 1.48 \times 10^{-4}$, $\tau_0 = 0.03$ mbarn^{-1}. $(^{107}{\rm Pd}/^{108}{\rm Pd})_{\rm PL}$ from iron meteorites used for calculating $\alpha_{107,108}(0)$; see WBGR. Prediction of other nuclei not yet established with $\bar{\tau} > 10^6$ yr for this AGB model is given in WBGR. For terms in curly braces, the subscript refers to observed values in CAIs and planetary differentiates (PL).

[a] ^{26}Al produced in H-burning shell of effective mass $M_{\rm H}/M_{\rm He} = 0.7$.

[b] ^{26}Al produced in H-burning shell of effective mass $M_{\rm H}/M_{\rm He} = 2.0$.

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1988; Straniero et al. 1994), which is only about a factor of 3 less than $\bar{\tau}_{41}$. For a 1.5 $M_{\odot}$ star, we estimate that the interpulse time in the most advanced pulses is $\sim 7 \times 10^5$ yr, in agreement with Boothroyd & Sackmann (1988).

For a stable or long-lived nucleus, the total amount produced and dredged up into the envelope during the whole TP-AGB phase is given by $N^{\rm DU} \Delta M_{\rm He} q^I_{\rm He}$, where $N^{\rm DU}$ is the total number of dredge-ups, $\Delta M_{\rm He}$ is the mass of the He shell involved in each dredge-up, and $q^I_{\rm He}$ is the number of the stable nucleus I produced per gram in the He convective shell. For ^{41}Ca, decay between pulses must be accounted for, so that the net number of ^{41}Ca in the envelope to be contributed to the ISM is given by

$$\sum_{m=1}^{N^{\rm DU}} \Delta M_{{\rm He},m}\, q^{40}_{{\rm He},m} (N^{41}_{\rm He}/N^{40}_{\rm He})_m \exp\left(-t_m/\bar{\tau}_{41}\right) , \quad (1)$$

where t_m is the time between the last pulse ($t_1 = 0$) to pulse m. Each term is evaluated at pulse m. For the case where the pulses are uniform and equally spaced (by Δt_p) and $t_m = (m-1)\Delta t_p$, then for a 3 $M_{\odot}$ star, $\Delta t_p = 0.3\bar{\tau}_{41}$, which yields

$$\sim 4\, \Delta M_{\rm He}\, q^{40}_{\rm He} \langle \sigma_{40} \rangle / \langle \sigma_{41} \rangle \quad (2)$$

and corresponds to a net of four effective pulses contributing ^{41}Ca. This approximately equals the result from the full numerical calculations. A typical 3 $M_{\odot}$ star undergoes nearly 20 dredge-up episodes before becoming a carbon star (Straniero et al. 1994). Thus, for ^{41}Ca, equation (2) is about one-fifth of the net contribution as compared to a long-lived or stable nucleus. In general, we found that the mass of the shell $\Delta M_{{\rm He},m}$ increases with the pulse number, from 2–3 $\times 10^{-4}$ $M_{\odot}$ to 1–2 $\times 10^{-3}$ $M_{\odot}$ in the last pulses for a 3 $M_{\odot}$ model (Busso et al. 1994). We estimate that the total contribution is bounded by the amounts assuming no decay and 0.2 times this value, considering decay for uniform dredged-up mass. For a 1.5 $M_{\odot}$ star, the longer interpulse period decreases the number of effective pulses to approximately 1.5 and will decrease the ^{41}Ca production by a factor of 2.6.

Following the approach of WBGR, assuming instantaneous injection, the contribution of AGB ejecta to the protosolar cloud is given by

$$\frac{M_{\rm SC}}{M_{\rm He}} \approx \left[\frac{N^R_{\rm He}/N^I_{\rm He}}{\alpha_{R,I}(0)}\right] \frac{q^I_{\rm He}}{q^I_{\rm SC}} , \quad (3)$$

where $M_{\rm SC}/M_{\rm He}$ is the ratio of the mass of the protosolar cloud to the mass of the contaminating He shell material, $q^I_{\rm He}$, $q^I_{\rm SC}$ are the numbers of I atoms per gram in the He shell or SC, and $\alpha_{R,I}(0)$ is the value of $(N^R_{\rm SC}/N^I_{\rm SC})$ in the contaminated cloud. As shown above, ^{41}Ca/^{40}Ca in the He shell is well defined, and the effective ^{41}Ca inventory contributed to the envelope is constrained by the bounds $f = 1$ to $f = 0.2$ times the He shell values listed. Assuming the initial q^I of the AGB star and of the $q^I_{\rm SC}$ to be nearly solar, then $q^{40}_{\rm He}/q^{40}_{\rm SC} \simeq 1$. For ^{41}Ca we then obtain

$$\alpha_{41,40}(0) \approx (M_{\rm He}/M_{\rm SC})(N^{41}_{\rm He}/N^{40}_{\rm He}) x f . \quad (4)$$

Using the dilution factor $M_{\rm He}/M_{\rm SC} = 1.5 \times 10^{-4}$ from WBGR for $\tau_0 = 0.03$ mbarn^{-1}, and $N^{41}_{\rm He}/N^{40}_{\rm He}$ (Table 2), we obtain $\alpha_{41,40}(0) = 1.5 \times 10^{-6} f$. Since the value of $\alpha_{41,40}(\Delta_1)$ is taken to be 1.5×10^{-8} from SUG at the time of CAI formation Δ_1, then $\Delta_1 = \bar{\tau}_{41} \ln [\alpha_{41,40}(0)/\, \alpha_{41,40}(t)] = 5 \times 10^5$ yr to 7×10^5 yr from the bounds on f.

From the proposed model, we infer a timescale (Δ_1) between 0.5 to 0.7 $\times 10^6$ yr from the time of injection of freshly synthesized material to collapse and formation of some CAIs. From considerations of possible changes in the parameters of this model, this timescale is well constrained because of the short mean-life of ^{41}Ca. This is somewhat shorter than the upper limit obtained from ^{26}Al($\Delta_1 < 2 \times 10^6$ yr). Setting a lower limit for Δ_1 from ^{26}Al is more difficult because of the uncertainties in estimates of the effective H-zone mass, $M_{\rm H}$, and the details of production/destruction of ^{26}Al in the H-He zone [see Table 2, footnotes (a) and (b)]. A direct comparison of the observed values of $\alpha_{R,I}(\Delta_1)$ at the time of formation of CAI is listed in Table 2 from the original calculation in WBGR, but recalculated to a value of $\Delta_1 = 0.5 \times 10^6$ yr instead of 1.0×10^6 yr. The range in $\alpha_{26,27}$ reflects the range in $M_{\rm H}/M_{\rm He} = 0.7$ to 2. It can be seen that there is, in general, very good agreement with the abundances of ^{41}Ca, ^{26}Al, ^{60}Fe, and ^{107}Pd.

3. CONCLUSIONS

We have shown that ^{41}Ca is a typical product of neutron captures in AGB stars with a production ratio in the He shell of ^{41}Ca/^{40}Ca $\approx 1 \times 10^{-2}$ and (0.3–1.5) $\times 10^{-4}$ in the AGB envelope. The results for an AGB source for ^{41}Ca (in conjunction with ^{26}Al, ^{60}Fe, and ^{107}Pd) implies a time $\Delta_1 =$ (5–7) $\times 10^5$ yr between the injection of debris into the ISM and the formation of CAIs (containing ^{26}Al and ^{41}Ca) and a time of $\sim 5 \times 10^6$ yr for the formation of planetary objects ($\sim 10^2$ km) containing ^{107}Pd and ^{60}Fe. It should be noted that the total mass (original envelope + He shell + H shell) of the AGB star that would be added to the solar system is $\sim 1 \times 10^{-2}$ $M_{\odot}$ and might be sufficient to initiate collapse within the placental molecular cloud. This model would require an AGB star with $\tau_0 \approx 0.03$ mbarn^{-1}, which is low compared to the main s-component for the solar system $\tau_0 \approx 0.30$ mbarn^{-1}. The low τ_0 requires some comment. AGB stars are the best candidates for synthesis of s-process isotopes beyond Zr. The main component is well reproduced with a mean neutron exposure $\tau_0 \approx 0.30$ mbarn^{-1} (Käppeler et al. 1990). This results from an average of mean neutron exposure of stars of different masses and metallicities (Gallino, Busso, & Raiteri 1994). Owing to the long lifetimes of low-mass stars, major contributions to s-process elements in the ISM at the epoch of solar system formation comes from stars of metallicity lower than solar ($Z \sim \frac{1}{3} Z_{\odot}$). For ^{13}C as the major neutron source, s-process neutron exposure decreases with increasing metallicity ($\tau_0 \sim 1/Z$) (see Clayton 1988). In conjunction with galactic chemical evolution models, the observation of a constant value of [Ba/Fe] versus [Fe/H] and of other s elements is a clear manifestation of this effect (Mathews, Bazan, & Cowan 1992; Gratton & Sneden 1994). This implies, for an AGB star of ~ 3 $M_{\odot}$ born of solar metallicity, that τ_0 will be much lower than for the main component. Direct evidence for low neutron exposures is also seen for M-type Mira stars showing Tc spectral lines and no other observed s-enhanced elements (Kipper 1991), a clear indication of ongoing s-processing with very low τ_0.

In our model we presume a close connection between an AGB star and the formation of the solar system. This may be a triggering mechanism as suggested by Cameron (1985, 1993) and would thus be a causal relationship. The probability of an encounter of an external AGB star with a molecular cloud is ~ 1% in 10^6 yr, and, over the life of a cloud, the probability of an encounter is high (Kastner & Myers 1994). It is also possible that an AGB star which formed and evolved inside the cloud could serve as the source of the short-lived nuclei. The cloud lifetime would require that the star be $\sim 5\ M_{\odot}$. We consider this as a possibility. Using the time of (0.5–0.7) $\times 10^6$ yr for the free-fall time implies a density of (4–8) $\times 10^3$ H cm^{-3} in the placental ISM. Both this result and that implied from ^{26}Al require that the triggering AGB star be close to the core of a dense molecular cloud. However, for the case of ^{26}Al, the timescale can only be given as $\sim 10^6$ yr, while with ^{41}Ca, there is no "free time" available. The timing implied is now so short that the dynamics of such injection mixing and collapse might be questioned.

We know that the ^{53}Mn present in the early solar system (Birck & Allègre 1985) cannot be attributed to an AGB source and requires another mechanism, possibly low-fluence proton bombardment of dust during T Tauri activity of the early Sun (Clayton, Dwek, & Woosley 1977; Wasserburg & Arnould 1987). While ^{41}Ca is abundantly produced in AGB stars with a well-fixed yield (^{41}Ca/^{40}Ca = $10^{-2}_{\sim}$), an alternative possibility is that the residual ^{41}Ca observed in CAIs is not that which was produced in an AGB star but is from a later distinct low-intensity source and was produced along with ^{53}Mn after the formation of the solar system. This would relax the extremely tight time constraint.

The possibility of other stellar sources for ^{107}Pd, ^{60}Fe, and ^{26}Al from massive stars or in connection with continuous supernova yields or a late supernova injection into a typical cloud must be considered. From the work of Weaver & Woosley (1993), the production ratio of ^{41}Ca/^{40}Ca is from 2.1×10^{-3} to 6.3×10^{-4} (for 15 to 35 $M_{\odot}$ stars). Alternatively, Clayton (1994) has proposed local cosmic rays in the placental molecular cloud as the source of these nuclei, based on the discovery of intense γ-ray sources in the Orion star-forming regions (Bloemen et al. 1994). The extent to which a self-consistent scenario for a supernova source or an intense cosmic-ray source is possible for these nuclei remains a subject of investigation.

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