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A TEST OF THE SUPERNOVA TRIGGER HYPOTHESIS WITH ^{60}Fe AND ^{26}Al

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ABSTRACT

It is shown that if the ^{26}Al inventory of the early solar system, taken as $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_\odot = 5 \times 10^{-5}$, is a result of injection of fresh debris from a Type II supernova (SNII), then ^{60}Fe/^{56}Fe would have to be between 3×10^{-7} and 1×10^{-5}. This inferred correlation of ^{26}Al and ^{60}Fe is based on the observation that both nuclei are produced dominantly in the O/Ne zone and that for SNII ejecta ^{26}Al/^{60}Fe is between 0.6 and 23. A similar correlation applies to ^{41}Ca, ^{36}Cl, ^{16}O, and ^{18}O, which are also produced in the same zone or in nearby regions. The supernova trigger hypothesis may be tested by determination of ^{60}Ni excesses correlated with Fe in samples where ^{26}Al was demonstrated to be present. From available experimental data, it appears that the observed abundance of ^{60}Fe is too low to be compatible with a supernova trigger that injected the ^{26}Al into the protosolar nebula. The same is true for ^{53}Mn, a short-lived nucleus produced in the outer edge of the Ni core.

Subject headings: ISM: abundances — nuclear reactions, nucleosynthesis, abundances — solar system: formation — stars: formation — supernovae: general

1. INTRODUCTION

The existence in the early solar system of short-lived radioactive nuclei (^{26}Al, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{129}I, ^{146}Sm, ^{182}Hf, ^{244}Pu) has provoked wide interest. A variety of stellar sources are required to produce these diverse nuclear species (cf. Cameron 1993). The timescale implied between production and injection into the protosolar nebula and the formation of condensed material processed by melting within the solar system (particularly for shorter lived nuclei) places severe constraints on any model. It has been suggested that the estimated early solar system inventory of ^{182}Hf, ^{244}Pu, and ^{146}Sm could well be provided by supernovae (SNs) with rather uniform production over galactic history (Wasserburg, Busso, & Gallino 1996, hereafter WBG96). However, this cannot account for ^{129}I, ^{107}Pd, and the shorter lived nuclei–in particular, ^{26}Al and ^{41}Ca. A variety of stellar sources have been considered: supernovae (Types Ia, Ib, and II; see, e.g., Cameron 1993; Cameron, Thielemann, & Cowan 1993; Cameron et al. 1995), asymptotic giant branch stars (AGB stars; see Wasserburg et al. 1994), novae (Truran 1982), and Wolf-Rayet stars (Arnould, Paulus, & Meynet 1997). It is also possible that some nuclei are produced by particle bombardment from the early Sun (Clayton & Jin 1995; Ramaty, Kozlovsky, & Lingenfelter 1995; Shu et al. 1997; Bateman, Parker, & Champagne 1996). One often cited scenario is of a late-stage SN trigger (Cameron & Truran 1977; Foster & Boss 1998; Cameron, Vanhala, & Höflich 1997), which caused the collapse of a cloud and injected freshly synthesized nuclear debris. This had some appeal as a source of ^{16}O found to be in excess (~4%) in Calcium-Aluminum–rich inclusions (CAIs) present in chondritic meteorites, which have been associated with condensates from hot portions of the solar nebula (Clayton, Grossman, & Mayeda 1973). An extensive study by Woosley & Weaver (1995, hereafter WW95) includes production of ^{26}Al and ^{60}Fe in SNII's. These workers calculated a range of models as a function of progenitor mass for metallicities (Z) from $Z_\odot$ to 0. Timmes et al. (1995, hereafter T+95), used these results to explore extensively relative contributions of ^{26}Al and ^{60}Fe to the ISM and γ-ray line fluxes in the Galaxy with emphasis on the rather constant ratio of ^{26}Al/^{60}Fe in different SNII models. Those SN models will be used here as a basis of estimating the possible relative contributions of ^{26}Al and ^{60}Fe to the placental solar nebula. As pointed out by A. G. W. Cameron (1997, private communication), a Wolf-Rayet source could trigger the collapse. In this case, the WR wind would have very high ^{26}Al/^{60}Fe. If the SNIb (with high ^{60}Fe) that subsequently formed did not inject matter into the protosolar nebula, this would decouple the production sites of ^{26}Al and ^{60}Fe. In this case, the test proposed here would not be valid.

2. PRODUCTION OF ^{26}Al AND ^{60}Fe IN SUPERNOVAE

As shown by WW95 and T+95, the major production of both ^{26}Al and ^{60}Fe is in the O/Ne zone. For example, in a 25 $M_\odot$ star with $Z_\odot$, 87% of the total ^{26}Al and 50% of the total ^{60}Fe is produced there. Insofar as these two nuclei are correlated, their relative contributions to the placental solar nebula are fixed and will not depend on details of shredding and mixing of zones in the SN explosion and the nature of the injection into the protosolar nebula. The mass yields $M(^{26}\mathrm{Al})$ ejected versus progenitor mass for $Z = Z_\odot$ ranges over a factor of 11 with a rather regular increase with mass reflecting the increasing extension of the O/Ne zone. $M(^{60}\mathrm{Fe})$ ranges over a factor of 36 but for $M > 13\ M_\odot$ the range is more restricted (factor of 5). The number ratio of ^{26}Al to ^{60}Fe as a function of SNII progenitor mass is shown in Figure 1*a*. The number ratio ^{26}Al/^{60}Fe ranges from 0.6 to 23. The average value is $\langle ^{26}\mathrm{Al}/^{60}\mathrm{Fe}\rangle = 8.5$. In supernova ejecta, a minor fraction of the ^{26}Al is present in the He/N zone produced during H-burning by $^{25}\mathrm{Mg}(p, \gamma)^{26}\mathrm{Al}$ from the original inventory of ^{25}Mg, so that production in this region is directly related to the metallicity. The major fraction of ^{26}Al is produced in the O/Ne zone by $^{25}\mathrm{Mg}(p, \gamma)^{26}\mathrm{Al}$ during hydrostatic convective shell C-burning, with protons mainly from $^{23}\mathrm{Na}(\alpha, p)^{26}\mathrm{Mg}$. There is a compe-

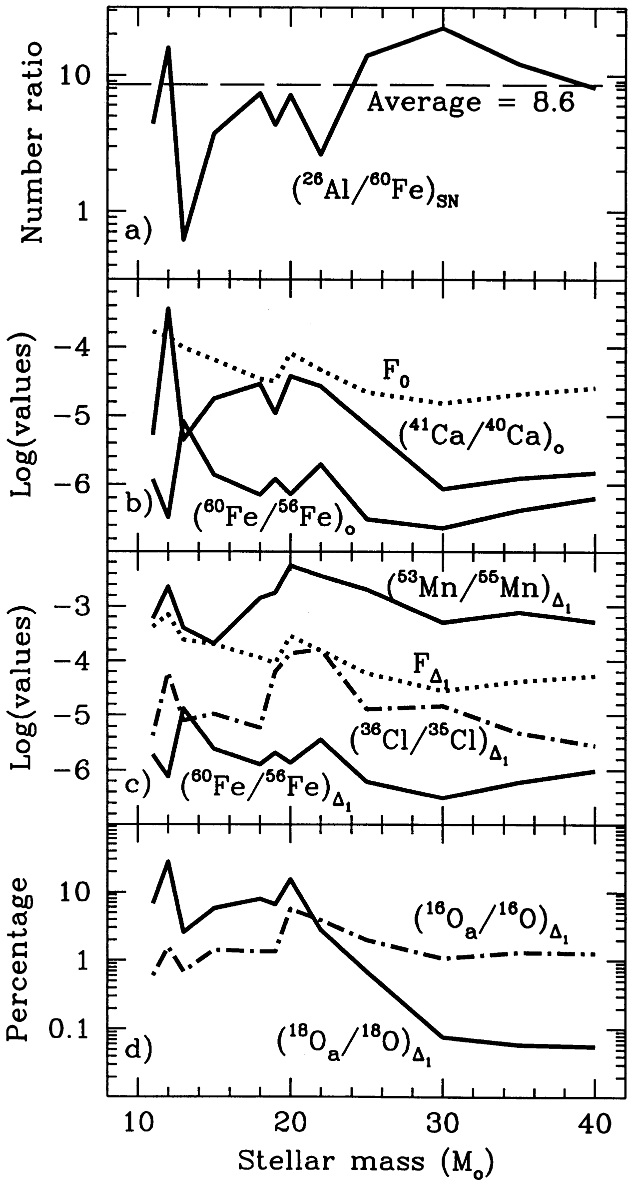

FIG. 1.—(*a*) Ratio of the number of ^{26}Al to ^{60}Fe produced in SNII's as a function of supernova mass; (*b*) Dilution factor F_0 to give $^{26}Al/^{27}Al = 5 \times 10^{-5}$ in the protosolar nebula at the time of explosion ($\Delta_1 = 0$) corresponding to values of $^{60}Fe/^{56}Fe$ and $^{41}Ca/^{40}Ca$ in the mixture; (*c*) Ratios corresponding to the time Δ_1 and the self-consistent dilution factor (for ^{26}Al and ^{41}Ca) at Δ_1; (*d*) Ratios of ^{16}O added from the SN to net $^{16}O_\odot$ and ^{18}O added to net solar $^{18}O_\odot$.

tition between ^{26}Al production by protons on ^{25}Mg and destruction by neutron or proton captures. We note that during the explosion, the ^{26}Al abundance in the O/Ne shell is enhanced, up to roughly 30% in the 25 $M_\odot$ case, by ν-nuclei inelastic collisions when protons liberated by ν-interactions on light nuclei are captured by ^{25}Mg (Woosley et al. 1990; WW95). The abundance of ^{25}Mg in this region is greatly enhanced owing to the conversion of the original inventory of CNO nuclei to $^{25}Mg + {}^{26}Mg$ through the chain CNO→^{14}N followed by $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O(\alpha, \gamma)^{22}Ne$, and by $^{22}Ne(\alpha, \gamma)^{26}Mg$ and $^{22}Ne(\alpha, n)^{25}Mg$. However, only a minor fraction of ^{25}Mg is consumed by proton capture. Note that, with a primary proton source, the production rate of a nucleus (^{26}Al) by proton capture on a secondary seed (^{25}Mg) that is not significantly depleted by the

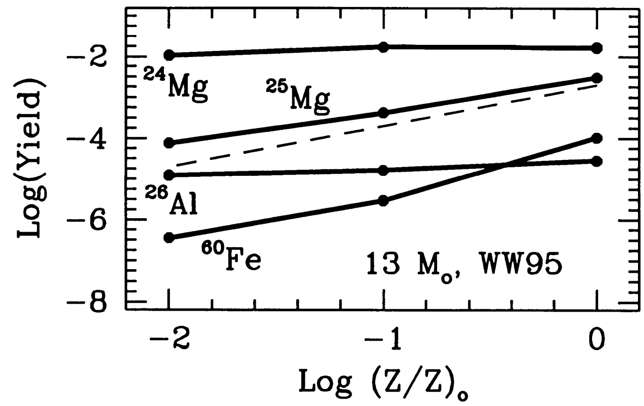

FIG. 2.—Mass yields of ^{24}Mg, ^{25}Mg, ^{26}Al, and ^{60}Fe from the 13 $M_\odot$ SN model by WW95 as a function of $Z/Z_\odot$. The dashed line of slope 1 shows the predicted trend of a purely secondary nuclide for reference.

bombardment is proportional to Z. If the protons are completely consumed on all the various target nuclei, the time integrated proton flux is proportional to $1/Z$. Thus, the resulting ^{26}Al yield is independent of Z.

Production of ^{60}Fe occurs partly in the He shell and partly in the O/Ne zone. In the He shell, ^{60}Fe is mostly produced by explosive nucleosynthesis through neutron captures from the original ^{56}Fe inventory, neutrons being released by the $^{22}Ne(\alpha, n)^{25}Mg$ reaction. The high peak temperature achieved by passage of the shock allows a high peak in the neutron density, so that the neutron channel to ^{60}Fe is favored with respect to β^--decay of ^{59}Fe ($\bar{\tau} = 65.1$ days). In preexplosive conditions a low abundance of ^{60}Fe was produced in this zone because of the low neutron density in hydrostatic phases, although the $^{22}Ne(\alpha, n)^{25}Mg$ reaction was already efficient during He shell burning. In the O/Ne region, ^{60}Fe is manufactured in the first stages of convective shell carbon-burning by neutron captures on the original ^{56}Fe owing to the high neutron density peak (Arnett & Truran 1969). A further enhancement occurs at the base of the O/Ne region by explosive nucleosynthesis when all residual ^{22}Ne is consumed. The ^{60}Fe yield is very small in less massive stars (11 and 12 $M_\odot$), where shock impact on the zone of interest is less pronounced. A sharp overproduction of ^{60}Fe instead occurs at $M = 13$ $M_\odot$, where a much higher neutron density is induced by shock heating in the O/Ne layers and in the C-rich neighboring region where a large gradient of partially burned He and a high abundance of ^{22}Ne are left by preexplosive phases.

We now explore the sensitivity of ^{26}Al and ^{60}Fe production as a function of Z using WW95. For the 13 $M_\odot$ model, the mass yields of ^{24}Mg, ^{25}Mg, ^{26}Al, and ^{60}Fe are shown in Figure 2, with a reference line of slope 1, corresponding to a nuclide whose production is dependent only on initial metallicity. For nuclei produced by a star from H and He (provided there are no structural modifications for a star of given mass with varying Z), the curve would be a horizontal line. This is roughly the case for ^{24}Mg. The yield of ^{25}Mg roughly parallels the trajectory of a purely secondary nuclide. For ^{60}Fe, the trend at lower Z corresponds to a purely secondary nuclide, but between $Z/Z_\odot = 1$ and 10^{-1} it is substantially steeper than the secondary trajectory. The ^{26}Al yield is almost independent of initial metallicity. We note that at $Z = 0$ (for cases in WW95 when the O/Ne zone is ejected and not ingested into a "black hole"), the yield of ^{26}Al is not very different from that of $Z = Z_\odot$, whereas

$M(^{60}\mathrm{Fe}) \approx 0$ at $Z = 0$. On average, trends of the yields exhibited for other SNII masses calculated by WW95 ($M/M_\odot = 11$–40) are in accord with the above considerations.

3. ^{60}Fe ABUNDANCE IN THE PROTOSOLAR NEBULA

We now address the question of $^{60}\mathrm{Fe}/^{56}\mathrm{Fe}$, which would be present in the protosolar nebula if ^{26}Al and ^{60}Fe were injected instantaneously from a SNII triggering the solar system. Then

$$(^{26}\mathrm{Al}/^{60}\mathrm{Fe})_{\mathrm{SN}} = (^{26}\mathrm{Al}/^{60}\mathrm{Fe})_0 = \frac{(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0(^{27}\mathrm{Al}_\odot)}{(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0(^{56}\mathrm{Fe}_\odot)} = 0.103\,\frac{(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0}{(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0}. \quad (1)$$

and

$$(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = \frac{27}{26}\,\frac{M(^{26}\mathrm{Al})}{5.8 \times 10^{-5}}\,\frac{1}{M_\odot}\,F_0. \quad (2)$$

Here F_0 is the dilution factor, i.e., the fraction of the mass $M(^{26}\mathrm{Al})$ ejected by the SN and instantaneously injected into the protosolar nebula and $M(^{27}\mathrm{Al}_\odot) = 5.8 \times 10^{-5}\ M_\odot$. $M(^{26}\mathrm{Al})$ is taken from WW95. With $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = 5 \times 10^{-5}$ (Lee, Papanastassiou, & Wasserburg 1977; McPherson et al. 1995) we calculate $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0$ for different masses (see Fig. 1*b*). The range is from 3×10^{-7} to the extreme of 8×10^{-6} (for 13 $M_\odot$). The average value is 1.4×10^{-6}. This value is much greater than the steady state level from SNs in the ISM of $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = 2.6 \times 10^{-8}$ (WBG96). F_0 (Fig. 1*b*, *dotted line*) ranges from 1.5×10^{-5} to 1.7×10^{-4}. Thus, if the inventory of ^{26}Al in the solar system is caused by instantaneous injection of SNII debris, then the initial abundance of ^{60}Fe must be very high. Hence, determination of $^{60}\mathrm{Fe}/^{56}\mathrm{Fe}$ in samples with ^{26}Al should provide a direct test of a SNII source. The average calculated $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0 = 1.4 \times 10^{-6}$ is far greater than the highest value of $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_{\mathrm{PD}} \sim 4 \times 10^{-9}$ found by Shukolyukov & Lugmair (1993a, 1993b) for the planetary differentiate (PD) Chervony Kut, while Juvinas gave $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe}) \sim 4 \times 10^{-10}$.

With regard to other SN types, we note that model W7 by Nomoto, Thielemann, & Yokoi (1984), usually taken as representative of SNIa predictions, produces $3.8 \times 10^{-5}\ M_\odot$ of ^{26}Al and only $2.3 \times 10^{-9}\ M_\odot$ of ^{60}Fe, with $(^{26}\mathrm{Al}/^{60}\mathrm{Fe}) = 3800$. This gives $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0 = 1.3 \times 10^{-9}$. Thus, SNIa's are not sources of concordant ^{26}Al and ^{60}Fe. SNIb,c types have been modeled by Woosley, Langer, & Weaver (1995) as very massive stars exploding after strong mass loss, or as less massive stars in a close binary mass-exchanging system exploding in a similar way. The calculated ^{26}Al and ^{60}Fe yields are nearly equal to the ones of a 25 $M_\odot$ SNII model.

4. TIMING THE SUPERNOVA TRIGGER BY ^{41}Ca

Using yields from WW95 and the dilution factor calculated from ^{26}Al, we show in Figure 1*b* the ratio $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0$. Production of ^{41}Ca occurs mainly in the O/Si inner zone by neutron capture on newly synthesized ^{40}Ca, a minor fraction coming from the outer O-rich and He/C zones by neutron capture on initial ^{40}Ca. Consequently, the ^{41}Ca yield nearly follows ^{40}Ca production and is roughly independent of metallicity. It is evident that the predicted $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0$ ratio is very high with respect to the value of 1.5×10^{-8} measured in CAIs by Srinivasan, Ulyanov, & Goswami (1994) and Sahijpal et al. (1998). Because of its very short lifetime, it is possible to reconcile ^{41}Ca and ^{26}Al by allowing a time delay Δ_1 between the explosion and formation of CAIs (assumed to be early condensates from the cloud by some unspecified heating mechanism).

As $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_{\Delta_1} = (^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0 e^{-\lambda_{41}\Delta_1}$ and $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\Delta_1} = (^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 e^{-\lambda_{26}\Delta_1}$, one obtains

$$\Delta_1 = \frac{1}{(\lambda_{41} - \lambda_{26})} \ln\Big\{[(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\Delta_1}/\ (^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_{\Delta_1}] \times [(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0/(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0]\Big\}. \quad (3)$$

For a self-consistent solution for ^{41}Ca and ^{26}Al at Δ_1 the dilution factor becomes $F_{\Delta_1} = F_0 \epsilon^{\lambda_{26}\Delta_1}$, with F_0 corresponding to instantaneous mixing as given in equation (2). F_{Δ_1} for different masses (see Fig. 1*c*) ranges from 2.8×10^{-5} to 7.1×10^{-4}. The delay Δ_1 is from 0.6 to 1.7 Myr. The lower limit is compatible with the value of Δ_1 estimated for the alternative hypothesis of an AGB source triggering collapse (Wasserburg et al. 1995).

Concerning other short-lived nuclei, values of $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_{\Delta_1}$, $(^{36}\mathrm{Cl}/^{35}\mathrm{Cl})_{\Delta_1}$, and $(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_{\Delta_1}$ are shown in Figure 1*c*. Production of ^{36}Cl strictly depends on production of ^{35}Cl, mimicking the behavior of ^{41}Ca with respect to ^{40}Ca, whereas production of ^{53}Mn occurs at the outer edge of the Ni core. The yields of all three isotopes are almost independent of metallicity. $(^{36}\mathrm{Cl}/^{35}\mathrm{Cl})_{\Delta_1}$ ranges between 3×10^{-6} and 2×10^{-4} and is compatible with the tentative $(^{36}\mathrm{Cl}/^{35}\mathrm{Cl}) = 1.4 \times 10^{-6}$ inferred by Murty, Goswami, & Shukolyukov (1997) from ^{36}Ar anomalies in the matrix of Efremovka that may possibly be caused by ^{36}Cl. Concerning ^{53}Mn, the results show $(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_{\Delta_1}$ ranging between 2.1×10^{-4} and 5.5×10^{-3}. These values are far above that found for $(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_{\mathrm{PD}}$ in planetary differentiates and above the value of 7×10^{-5} estimated from some CAI samples (Birck & Allègre 1985). The lowest value is close to the steady state ratio in the ISM (WBG96). However, the question of ^{53}Mn is more complex as this nucleus is produced in the outer edge of the Ni core and is thus dependent on the "piston" location (WW95).

There are interesting consequences on the associated oxygen isotopes in the SN debris. Both ^{16}O and ^{18}O are abundantly produced. ^{18}O is produced in the C-rich zone adjacent to the O/Ne zone, and its production depends linearly on metallicity, whereas ^{17}O is severely underproduced (Woosley et al. 1997). It is thus of interest to estimate contributions associated with ^{26}Al. Figure 1*d* shows the ratios of ^{16}O and ^{18}O added (along with ^{26}Al) relative to the solar inventory of $^{16}\mathrm{O}_\odot$ and $^{18}\mathrm{O}_\odot$. The fractional contribution for $^{16}\mathrm{O}_{\mathrm{SN}}$ to solar oxygen ranges from 0.60% (for $M = 12\ M_\odot$) to 5.7% (for $M = 20\ M_\odot$) and $^{18}\mathrm{O}_{\mathrm{SN}}$ ranges from 0.056% (for $M = 40\ M_\odot$) to 27.4% (for $M = 12\ M_\odot$). We note that for $M = 11$–22 $M_\odot$, the fractional shifts are larger for ^{18}O than for ^{16}O. However, for $M = 30$–40 $M_\odot$ the dominant effect is for $^{16}\mathrm{O}_{\mathrm{SN}}$ addition of ~l% with only much smaller effects on ^{18}O.

5. DISCUSSION AND CONCLUSION

Since ^{60}Fe has been found in eucrites that are debris of planetary differentiates formed at later times with respect to CAIs, we introduce a further time interval Δ_2, for which

$$({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\Delta_1+\Delta_2} = ({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_0 e^{[(\lambda_{26}-\lambda_{60})\Delta_1-\lambda_{60}\Delta_2]}. \quad (4)$$

The range of $({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\Delta_1}$ is from 3.2×10^{-7} to 1.3×10^{-5} ($\bar{\tau}_{^{60}\mathrm{Fe}} = 2.16 \times 10^6$ yr; Kutschera et al. 1984). If $({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\mathrm{PD}} = 4 \times 10^{-9}$ evolved from $({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\Delta_1}$, this gives Δ_2 between 9.5 and 18 Myr, at which times there would be no ^{26}Al present. If Δ_2 were actually much less than these values, then a SNII source would be excluded. The issues are then: when did the planetary processes take place that fractionated Fe from Ni, and, how do these timescales connect with the earliest recorded nebular events? Assuming an isotopically homogeneous initial state for the solar nebula, there are refined relative chronologies for several planetary differentiates from ^{107}Pd, ^{53}Mn, and ^{182}Hf. However, the precise time linkage to an initial nebular state is not well known. We note that indications of isotopic heterogeneities in the early solar nebula on a small and possibly on a large scale clearly exist. While substantial studies have been made to establish an absolute timescale for CAIs and planetary differentiates using U-Th-Pb, Pb-Pb, Rb-Sr, Re-Os, K-Ar, and Sm-Nd methods, we do not consider that any of these efforts have succeeded in establishing an absolute chronology of sufficient precision to determine time differences of formation (not metamorphism) relative to an initial state of the solar nebula of a few million years at 4.56 Gyr ago. If Δ_2 for the planetary differentiates investigated is less than 9 Myr, then a late SNII injection is incompatible with the $({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\mathrm{PD}}$ obtained by Shukolyukov & Lugmair (1993a, 1993b) (see also Lugmair, Shukolyukov, & MacIsaac 1996). However, there are no direct measurements on materials with evidence of both ^{26}Al and ^{60}Fe. Isotopic anomalies in Ni were discovered by Birck & Lugmair (1988) on CAIs. It is very plausible that ^{26}Al might be present in these CAIs, although no determination was made. These samples show isotopic anomalies in ^{60}Ni, ^{62}Ni, and ^{64}Ni as well as in ^{53}Cr and ^{54}Cr for the normalizations used. It follows that these samples have not quite been isotopically homogenized to bulk solar value. These authors attributed the general Ni anomalies to contributions from neutron-rich statistical equilibrium. Isotopic shifts in ^{57}Fe and ^{58}Fe found in other CAIs by Völkening & Papanastassiou (1989) also indicate such a source. It is thus not clear whether the effects observed in ^{60}Ni are a result of ^{60}Fe decay or to general isotopic anomalies. No correlation of ^{60}Ni excess with Fe have been made in CAIs. As pointed out by Birck & Lugmair (1988), if the ^{60}Ni excess in one Ni-rich sample is attributed to ^{60}Fe, then an upper limit of $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = 1.6 \times 10^{-6}$ is obtained. This value is near or just at the lower limit of $({}^{60}\mathrm{Fe}/{}^{56}\mathrm{Fe})_{\Delta_1}$ given above. We conclude that a clear test of the SNII injection hypothesis is to measure Ni for samples containing ^{26}Mg excess from ^{26}Al decay and where a correlation of ^{60}Ni excess is made with Fe. We note that for $({}^{60}\mathrm{Ni}/{}^{56}\mathrm{Fe})_\odot = 0.0156$, the shifts expected for the SN trigger and injection model should correspond to increases of 0.2–8.3 εu in ^{60}Ni (1 εu = 1 part per 10,000). Enrichments of Fe/Ni in mineral phases of only a factor of 10 above solar should demonstrate clear-cut effects that may be tested in both CAIs and also in chondrules which have high Fe/Ni phases if they were formed in the first three million years. If $({}^{26}\mathrm{Al}/{}^{60}\mathrm{Fe})_\odot = 8.5$, then the total thermal energy from ^{60}Fe relative to ^{26}Al is 2.78 MeV/(3.10 MeV $\times$ 8.5) = 1.1×10^{-1} and thermal effects are governed by ^{26}Al. After 2.2×10^6 yr, there is still sufficient heat to raise an insulated body of chondritic composition to $\sim 10^3$ K. A planetary iron core produced by early melting from ^{26}Al would have abundant ^{60}Fe and would provide a major heat source in the core for a dynamo ($\sim 2 \times 10^3$ J g^{-1}) or a peak heating rate of $\sim 10^{-3}$ J g^{-1} yr^{-1}).

With regard to ^{53}Mn, this isotope is produced in great abundance by SNII's, and $({}^{53}\mathrm{Mn}/{}^{55}\mathrm{Mn})_{\Delta_1}$ is in excess of the highest initial estimate of 6.7×10^{-5} by Birck & Allègre (1985) on CAIs. The ^{53}Mn is produced interior to the O/Ne zone, and $M(^{53}\mathrm{Mn})$ is sensitive to the radius at which the overlying mass is ejected. It may be possible to decrease the ^{53}Mn contribution by a higher "piston position" or by assuming that the ejected mass from the core is not well mixed with the O/Ne zone material. The ^{56}Ni contributions inferred for SN 1987A (Shigeyama, Nomoto, & Hashimoto 1988; Woosley 1988; Arnett & Fu 1989) indicate that core material was ejected in standard proportions. It is thus not evident that significant shifts in the piston position are justifiable.

With regard to oxygen, we note that for progenitor masses less than 20 $M_\odot$, the fractional contribution of ^{18}O exceeds that of ^{16}O so that effects of such admixture would be to shift the ^{18}O much more than for ^{16}O. Adopting the ^{41}Ca and ^{26}Al "concordance" time interval of Δ_1 then for masses greater than 25 $M_\odot$, it is possible to obtain shifts of ^{16}O at the 1% level with no major effects on ^{18}O. Lower mass supernovae would not provide this effect. In the case of 12 $M_\odot$, a 30% contribution to the solar system ^{18}O inventory but a much smaller ^{16}O contribution might explain the high $({}^{18}\mathrm{O}/{}^{17}\mathrm{O})_\odot = 5.5$ compared to $({}^{18}\mathrm{O}/{}^{17}\mathrm{O})_{\mathrm{ISM}} = 3.5$ (Penzias 1981). The much debated explanation of the problem of ^{16}O excesses discovered by Clayton, Grossman, & Mayeda (1973) throughout samples of condensed matter in the solar system (cf. Clayton 1993) remains unclear as these excesses are not correlated with other nuclear anomalies. If the excess ^{16}O is from a fresh SNII source, there should be associated anomalies of both radioactive and stable nuclei from the O/Ne zone in the samples with large ^{16}O excesses. The consequences of the SN trigger hypothesis on other isotopic shifts will be reported on in a more extensive report.

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