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^{60}Fe IN CHONDRITES: DEBRIS FROM A NEARBY SUPERNOVA IN THE EARLY SOLAR SYSTEM?

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ABSTRACT

^{60}Fe decays to ^{60}Ni with a half-life of 1.49×10^6 yr, so all of the original ^{60}Fe atoms incorporated into the solar system have decayed. Because ^{60}Fe is produced only in stars, its initial abundance in the solar system provides a constraint on the stellar contribution of radionuclides to the early solar system and on the nature of the stellar source. Because of its short half-life, ^{60}Fe is also a potential high-resolution chronometer of early-solar-system events. The presence of ^{60}Fe in primitive meteorites has been confirmed in sulfides, but the initial abundance of ^{60}Fe in the solar system has been only loosely constrained because it is uncertain when the sulfides formed. We show that ^{60}Fe was present with abundance ratios of ^{60}Fe/^{56}Fe = (2.2–3.7) $\times 10^{-7}$ when ferromagnesian chondrules formed. By applying the time difference of 1.5–2.0 million years between formation of ferromagnesian chondrules and Ca-Al-rich inclusions (CAIs), the oldest known solar system solids, a solar system initial ^{60}Fe/^{56}Fe ratio [(^{60}Fe/^{56}Fe)$_0$] of (5–10) $\times 10^{-7}$ is estimated. This new solidly based (^{60}Fe/^{56}Fe)$_0$ ratio is consistent with predictions for nucleosynthesis in a supernova or in an intermediate-mass asymptotic giant branch (AGB) star just before the solar system formation, but is too high for the source to have been a low-mass AGB star. Considering the rarity of encounters between a molecular cloud and an AGB star, our results can be considered strong evidence of a contribution of material from a nearby supernova and of a role for a supernova in the origin of the solar system.

Subject headings: methods: analytical — nuclear reactions, nucleosynthesis, abundances — solar system: formation

1. INTRODUCTION

Isotopic analyses of meteorites have revealed that several short-lived radionuclides once existed in the solar system (e.g., ^{41}Ca, ^{36}Cl, ^{26}Al, ^{60}Fe, ^{10}Be, ^{53}Mn; Kita et al. 2005a). They are produced either by stellar nucleosynthesis or by energetic-particle irradiation. ^{10}Be cannot be produced in stars, so its presence in the early solar system indicates a contribution from energetic-particle irradiation (McKeegan et al. 2000). On the other hand, because ^{60}Fe is produced exclusively in stars, stellar nucleosynthesis also contributed to the solar system short-lived radionuclides.

Hints of ^{60}Fe in the solar system first came from excesses of ^{60}Ni in CAIs (Birck & Lugmair 1988). But the ^{60}Ni excesses were not correlated with the Fe/Ni ratio, and the inclusions also exhibited anomalies in other Ni isotopes, so the evidence that ^{60}Fe was present was ambiguous. The first evidence of live ^{60}Fe in the solar system was found in differentiated meteorites, which experienced significant melting and thermal metamorphism in their parent body (Shukolyukov & Lugmair 1993). The initial solar system ^{60}Fe/^{56}Fe ratio [(^{60}Fe/^{56}Fe)$_0$] inferred from these meteorites was quite low ($\ll 10^{-7}$) and could be explained by the steady state abundance of ^{60}Fe in the interstellar medium (Wasserburg et al. 1996). Several attempts to find evidence of ^{60}Fe in primitive chondrites, those that experienced neither significant heating nor significant aqueous alteration after accretion, were unsuccessful (Choi et al. 1999; Kita et al. 2000). Clear evidence of ^{60}Fe in chondrites was first found in troilite (FeS) and magnetite (Fe_3O_4) (Tachibana & Huss 2003; Mostefaoui et al. 2005). The inferred (^{60}Fe/^{56}Fe)$_0$ ratios for these minerals range from (1–1.8) $\times 10^{-7}$ for sulfides from the Bishunpur and Krymka (LL3.1) chondrites (Tachibana & Huss 2003) to 9.2×10^{-7} for sulfides from Semarkona (LL3.0) (Mostefaoui et al. 2005). Although it is uncertain when those sulfides formed, if sulfides are assumed to have formed 1–2 Myr after the CAI formation, the (^{60}Fe/^{56}Fe)$_0$ ratio for the solar system would have been in the range of (3–16) $\times 10^{-7}$. These ratios require a stellar input just before or during solar system formation. The type of stellar source for the ^{60}Fe can be constrained by the initial abundance of ^{60}Fe in the solar system, but the relatively loose constraint from chondritic sulfides permits both low- and high-mass stars to be the source of ^{60}Fe. To make matters worse, the ^{60}Fe-^{60}Ni system in sulfides is easily disturbed by mild thermal metamorphism on the parent body (Guan et al. 2004). The ^{60}Fe-^{60}Ni system in sulfides may record later parent-body processing even in the least metamorphosed chondrites rather than events that occurred 1–2 Myr after CAIs. Thus, estimating (^{60}Fe/^{56}Fe)$_0$ for the initial solar system from sulfides may not be reliable.

Chondrules are major silicate constituents in chondrites, and their formation times have been dated independently using the ^{26}Al-^{26}Mg and Pb-Pb chronometers to be ~1–2 Myr after the CAI formation (Kita et al. 2000, 2005b; Amelin et al. 2002). Most chondrules formed by melting and subsequent rapid cooling during transient high-temperature events in the early solar system. Silicates are much less susceptible to thermal metamorphism and aqueous alteration than sulfides, so chondrule silicates should preserve the ^{60}Fe/^{56}Fe ratio at the time of chondrule formation. In this work, we used an ion microprobe to search for evidence of ^{60}Fe in four chondrules containing pyroxene [(Mg, Fe)SiO_3] with high Fe/Ni ratios from two of the least metamorphosed ordinary chondrites, Semarkona (LL3.0) and Bishunpur (LL3.1).

2. MEASUREMENTS

Thin sections of Semarkona and Bishunpur were examined using a scanning electron microscope equipped with an energy-

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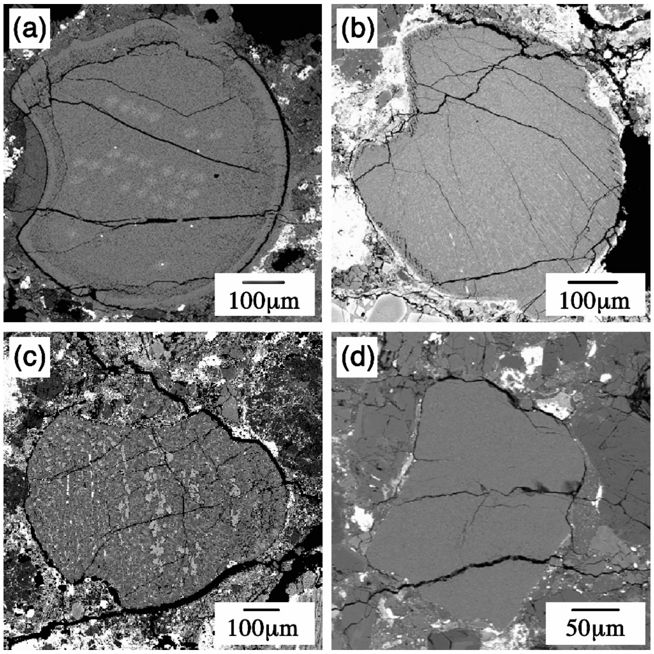

FIG. 1.—Backscattered electron images of pyroxene-rich chondrules with high Fe/Ni ratios in Semarkona (SMK1-4, SMK2-1, and SMK2-4) and Bishunpur (BIS-21). (*a*) SMK1-4. (*b*) SMK2-1. (*c*) SMK2-4. (*d*) BIS-21.

dispersive spectrometer (EDS) to identify chondrules with FeO-rich silicates. Because Ni contents in silicates suitable for this study are way below the detection limit of an EDS, Fe/Ni ratios of chondrule silicates were checked using the Cameca ims-6f ion microprobe at Arizona State University. We selected four ferromagnesian chondrules containing abundant pyroxene [(Mg, Fe)SiO_3] with Fe/Ni elemental ratios up to $\sim 3 \times 10^4$ and hints of ^{60}Ni excesses for detailed isotopic analysis (Fig. 1).

The ^{60}Fe-^{60}Ni systems in chondrules were analyzed using the Cameca ims-1270 ion microprobe at the Geological Survey of Japan. A Kohler-illuminated, ~15 μm, 1 nA, primary O_2^- beam was used to sputter the samples. The secondary mass spectrometer was operated at 10 kV with a 50 eV energy window and a mass resolving power (MRP) of ~4500. Secondary ions ($^{57}Fe^+$, $^{60}Ni^+$, $^{61}Ni^+$, and $^{62}Ni^+$) were counted on an electron multiplier in monocollection mode. Detailed conditions were described previously (Kita et al. 1998, 2000). Although an MRP of 4500 is insufficient to resolve interferences from hydrides and molecular ions of oxides ($^{44}Ca^{16}O$, $^{45}Sc^{16}O$, and $^{46}Ti^{16}O$), the contributions of such interferences were confirmed to be ≤1‰. The Fe/Ni sensitivity factor obtained for KL2-G basalt glass was used [$(Fe/Ni)_{true}/(Fe/Ni)_{measured} = \sim 0.7$] because it most closely matches the mixture of pyroxene and interstitial glassy mesostasis that was measured in the chondrules. Instrumental mass fractionation for the measured $^{60}Ni/^{61}Ni$ was corrected internally using $^{62}Ni/^{61}Ni$.

3. RESULTS

Isotopic analyses show clear excesses of ^{60}Ni in all four chondrules (Table 1). Chondrule SMK1-4 (Fig. 1*a*) is a fine-grained radiating pyroxene chondrule with a pyroxene composition of $En_{\sim 61}$ [$=(Mg_{\sim 0.61}, Fe_{\sim 0.39})SiO_3$] from Semarkona. For this chondrule, data obtained with the Cameca ims-6f ion microprobe (Huss & Tachibana 2004), shown as weighted means of several analyses, are consistent with those obtained by single-spot analyses using the ims-1270 (Fig. 2*a*). Excesses

TABLE 1

Fe-Ni ISOTOPE DATA FOR PYROXENE-RICH CHONDRULES

$^{56}Fe/^{61}Ni$ ($\times 10^6$)	δ^{60}Ni[a] (‰)	$^{60}Ni/^{61}Ni$	Correlation Coefficient[b]
Chondrule SMK1-4			
0.0020 ± 0.0002[c]	0.3 ± 1.9	23.11 ± 0.04	0.04
0.0040 ± 0.0004[c]	−0.5 ± 2.4	23.09 ± 0.06	0.03
0.348 ± 0.038	1.6 ± 8.8	23.14 ± 0.20	0.17
0.593 ± 0.048	5.8 ± 8.9	23.23 ± 0.20	0.27
0.595 ± 0.050	6.4 ± 7.9	23.25 ± 0.18	0.24
0.936 ± 0.103	22 ± 12	23.60 ± 0.28	0.13
1.34 ± 0.11	11 ± 11	23.35 ± 0.26	0.34
1.54 ± 0.17	16 ± 11	23.47 ± 0.25	0.19
1.64 ± 0.13	20 ± 14	23.57 ± 0.31	0.42
1.88 ± 0.16	27 ± 16	23.73 ± 0.37	0.42
1.89 ± 0.15	18 ± 14	23.51 ± 0.32	0.42
1.93 ± 0.16	16 ± 14	23.46 ± 0.32	0.41
Chondrule SMK2-1			
0.0017 ± 0.0002[c]	1.6 ± 1.7	23.14 ± 0.04	0.02
1.22 ± 0.14	9.2 ± 23	23.31 ± 0.54	0.51
1.41 ± 0.11	25 ± 25	23.67 ± 0.57	0.67
1.49 ± 0.12	18 ± 20	23.52 ± 0.46	0.57
1.81 ± 0.19	10 ± 19	23.33 ± 0.43	0.45
1.89 ± 0.21	18 ± 20	23.52 ± 0.46	0.42
2.63 ± 0.28	26 ± 23	23.71 ± 0.53	0.46
2.64 ± 0.19	34 ± 39	23.89 ± 0.90	0.81
2.70 ± 0.22	35 ± 30	23.91 ± 0.70	0.74
Chondrule SMK2-4			
0.00030 ± 0.00002[c]	1.7 ± 4.4	23.14 ± 0.10	0.08
0.182 ± 0.014	−4.3 ± 7.6	23.00 ± 0.17	0.26
0.188 ± 0.020	7.3 ± 14	23.27 ± 0.32	0.31
0.449 ± 0.036	1.9 ± 10	23.14 ± 0.23	0.32
1.18 ± 0.10	22 ± 20	23.60 ± 0.47	0.54
1.42 ± 0.13	15 ± 19	23.44 ± 0.44	0.56
1.74 ± 0.16	32 ± 30	23.84 ± 0.70	0.66
Chondrule BIS-21			
0.015 ± 0.002	0.4 ± 3.5	23.11 ± 0.08	0.09
0.358 ± 0.025	1.4 ± 12	23.13 ± 0.28	0.40
0.399 ± 0.028	5.4 ± 13	23.23 ± 0.31	0.45
0.407 ± 0.035	5.6 ± 13	23.23 ± 0.31	0.38
1.64 ± 0.14	40 ± 24	24.03 ± 0.55	0.60
1.76 ± 0.12	18 ± 26	23.51 ± 0.60	0.69
2.01 ± 0.17	33 ± 31	23.86 ± 0.71	0.68

NOTE.—All errors are 2 σ.

[a] Excesses of ^{60}Ni are expressed by $\delta^{60}Ni\ (‰) = \Delta^{60}Ni - (-\Delta^{62}Ni)$, where $\Delta^{m}Ni\ (‰) = \{[(^{m}Ni/^{61}Ni)_{sample}/(^{m}Ni/^{61}Ni)_{normal}] - 1\} \times 1000$ ($m = 60,\ 62$). The $(^{m}Ni/^{61}Ni)_{normal}$ values are 23.100 for $m = 60$ and 3.1760 for $m = 62$.

[b] Correlation coefficients between errors for $^{56}Fe/^{61}Ni$ and $^{60}Ni/^{61}Ni$.

[c] Phases containing metals and/or sulfides.

of ^{60}Ni are correlated with $^{56}Fe/^{61}Ni$, and the $(^{60}Fe/^{56}Fe)_0$ ratio inferred for this chondrule is $(2.7 \pm 0.8) \times 10^{-7}$. Chondrule SMK2-1 is also a fine-grained radiating pyroxene chondrule from Semarkona with Fe-Mg compositional zoning in radiating pyroxene bars from $En_{\sim 90}$ near the center to $En_{\sim 85}$ at the edge (Fig. 1*b*). ^{60}Ni excesses correlate with $^{56}Fe/^{61}Ni$, and the inferred $(^{60}Fe/^{56}Fe)_0$ ratio is $(2.2 \pm 1.0) \times 10^{-7}$ (Fig. 2*b*). Chondrule SMK2-4 is a barred pyroxene chondrule with Fe-rich olivine grains ($Fo_{\sim 70}$ [$=(Mg_{\sim 0.7}, Fe_{\sim 0.3})_2SiO_4$]) between the bars. Pyroxene bars show zoning from $En_{\sim 85}$ near the center to $En_{\sim 75}$ at the edge (Fig. 1*c*). SMK2-4 also shows ^{60}Ni excesses, and its inferred $(^{60}Fe/^{56}Fe)_0$ ratio is $(2.8 \pm 2.1) \times 10^{-7}$ (Fig. 2*c*). BIS-21 is an irregular-shaped fine-grained pyroxene chondrule, which may be a fragment of a larger chondrule, with a pyroxene composition of $En_{\sim 75}$ from Bishunpur (Fig. 1*d*). BIS-21 gives an inferred $(^{60}Fe/^{56}Fe)_0$ ratio of $(3.7 \pm 1.9) \times 10^{-7}$ (Fig. 2*d*). The $(^{60}Fe/^{56}Fe)_0$ ratios inferred for the four chondrules [$(2.2 \pm 1.0) \times 10^{-7}$–$(3.7 \pm 1.9) \times 10^{-7}$] are consistent with

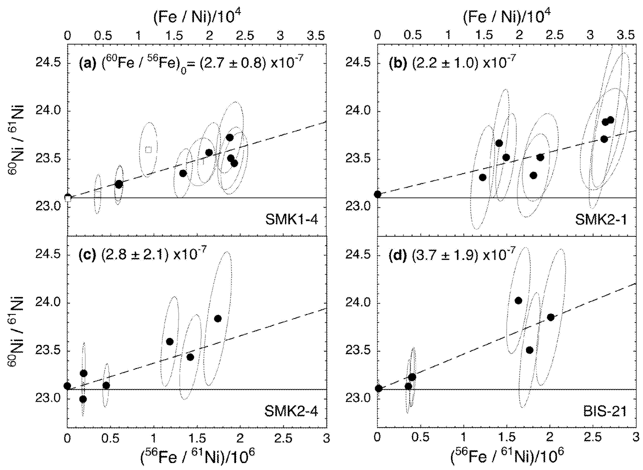

FIG. 2.—Isochron diagrams of ^{60}Fe-^{60}Ni system in FeO-rich pyroxene chondrules in Semarkona and Bishunpur. The presence of now-extinct ^{60}Fe in an early-solar-system object is demonstrated by a correlation between the abundance of radiogenic ^{60}Ni and the Fe/Ni elemental ratio. In an undisturbed object, the relative abundance of ^{60}Fe to stable ^{56}Fe at the time the object formed, $(^{60}Fe/^{56}Fe)_0$, can be obtained from the slope of a linear correlation between $^{60}Ni/^{61}Ni$ and $^{56}Fe/^{61}Ni$, because $(^{60}Ni/^{61}Ni) = (^{60}Ni/^{61}Ni)_0 + (^{60}Fe/^{56}Fe)_0 \times (^{56}Fe/^{61}Ni)$. Counting statistics for ^{61}Ni make a large contribution to the errors on the isotope ratios, and because this is a correlated error, the 2 σ uncertainty for each data point is shown as an error ellipse. The Fe/Ni weight ratio is also shown on the top horizontal axis. (*a*) SMK1-4. Open squares are data obtained by the ASU Cameca ims-6f as weighted means of several measurements (Huss & Tachibana 2004). (*b*) SMK2-1. (*c*) SMK2-4. (*d*) BIS-21.

a single value within analytical uncertainties, but the uncertainties also permit the initial ratios to differ by almost a factor of 2. The $(^{60}Fe/^{56}Fe)_0$ ratios for the chondrules are larger than those obtained for sulfides in Bishunpur and Krymka (Tachibana & Huss 2003) and for magnetite in Semarkona (Mostefaoui et al. 2005), but are smaller than that inferred for Semarkona sulfides (Mostefaoui et al. 2005).

4. DISCUSSION

4.1. ^{60}Fe-^{60}Ni *System in Chondrules from the Least Metamorphosed Ordinary Chondrites*

Semarkona and Bishunpur are among the least metamorphosed ordinary chondrites (Grossman & Brearley 2005). They have experienced metamorphic temperatures no higher than ~530 and ~570 K, respectively (Rambaldi & Wasson 1981; Alexander et al. 1989; Huss & Lewis 1994). Although no data are available for Ni diffusion in low-Ca pyroxene, if we extrapolate Fe-Mg diffusion rates in low-Ca pyroxene (Ganguly & Tazzoli 1994) to the metamorphic temperatures for Semarkona and Bishunpur, we would not expect cation diffusion to significantly affect the ^{60}Fe-^{60}Ni system in even micron-sized pyroxene grains (smaller than the measured area) during 10 Myr of metamorphism. The Mg-Fe zoning in pyroxene for SMK2-1 and SMK2-4 supports this expectation. Thus, the $(^{60}Fe/^{56}Fe)_0$ ratio for each chondrule most likely represents the last melting event, which occurred prior to parent-body accretion.

If the $(^{60}Fe/^{56}Fe)_0$ ratios inferred for the chondrules represent their formation times, then the lower $(^{60}Fe/^{56}Fe)_0$ ratios inferred for troilites in Bishunpur and Krymka [$(1–1.8) \times 10^{-7}$; Tachibana & Huss 2003] and for magnetites in Semarkona (1.4×10^{-7}; Mostefaoui et al. 2005) probably reflect mild thermal metamorphism and aqueous alteration on the parent bodies, which occurred ~1–2 Myr after chondrule formation. This interpretation is consistent with the more rapid diffusion of Fe and Ni in sulfides (Condit et al. 1974; Lauretta 2005) and with the secondary origin of magnetite and some sulfides by aqueous alteration on the Semarkona parent body (Krot et al. 1997).

Alternatively, if the $(^{60}Fe/^{56}Fe)_0$ ratio for Semarkona troilite (9.2×10^{-7}; Mostefaoui et al. 2005) is taken at face value, it implies that Semarkona troilites formed ~2–4 Myr earlier than the chondrules. The ^{26}Al-^{26}Mg chronometer has shown that many chondrules in Semarkona and Bishunpur experienced the last melting events ~1.5–2.0 Myr after CAIs (Kita et al. 2000, 2005b; Mostefaoui et al. 2002). Tying the ^{60}Fe chronometer to that of ^{26}Al implies that the Semarkona troilites are older than CAIs and are thus the oldest objects in the solar system. However, S is more volatile than refractory elements such as Ca and Al, and its bulk abundance in Semarkona is depleted compared to the CI abundance (~0.25 × CI) (Jarosewich 1990). This indicates that S in the Semarkona parent material was mobilized and fractionated due to partial evaporation or incomplete condensation and that many Semarkona sulfides formed well after the CAI-forming epoch. Our preferred interpretation is that the high ratios in Semarkona troilites reflect disturbance of the Fe-Ni systematics. Semarkona troilites may have lost iron during the parent-body aqueous alteration that formed magnetite, resulting in a higher slope for the isochron.

4.2. *Initial Abundance of* ^{60}Fe *in the Solar System and Its Probable Stellar Source*

We can estimate the initial $(^{60}Fe/^{56}Fe)_0$ for the solar system by correcting our measured $(^{60}Fe/^{56}Fe)_0$ for the chondrules for the ~1.5–2.0 Myr time delay before the chondrules formed. From this correction, we estimate $(^{60}Fe/^{56}Fe)_0$ for the solar system to have been $(5–10) \times 10^{-7}$, a significantly tighter constraint than provided by previous data from sulfides (Tachibana & Huss 2003; Mostefaoui et al. 2005). Our estimated $(^{60}Fe/^{56}Fe)_0$ ratio, the inferred $(^{26}Al/^{27}Al)_0$ ratio (5×10^{-5}) and abundances for other short-lived radionuclides estimated for the initial solar system (e.g., ^{41}Ca) can be compared with the model-predicted abundance ratios for nucleosynthesis for different types of stars, allowing time for the nuclides to enter the solar system. Nonexploding Wolf-Rayet stars cannot produce the estimated initial $(^{60}Fe/^{56}Fe)_0$ at all [$(^{60}Fe/^{56}Fe)_0 \ll (1–2) \times 10^{-8}$; Arnould et al. 1997]. Models for nucleosynthesis in low-mass AGB stars predict $(^{60}Fe/^{56}Fe)_0$ up to a few $\times 10^{-7}$, insufficient to explain the $(^{60}Fe/^{56}Fe)_0$ ratio estimated from the chondrules (Wasserburg et al. 1994, 2006). Models for intermediate-mass AGB stars (5 $M_\odot$ with solar metallicity or 3 $M_\odot$ with $\frac{1}{3}$ solar metallicity) predict $(^{60}Fe/^{56}Fe)_0$ of $(1–2) \times 10^{-6}$ for the initial solar system, consistent with our estimates (Wasserburg et al. 2006). However, the rarity of encounters between molecular clouds and AGB stars (probability of $<3 \times 10^{-6}$; Kastner & Meyers 1994) makes it implausible for an AGB star to be a source of short-lived radionuclides. Moreover, AGB stars cannot produce enough ^{53}Mn to explain the estimated initial abundance of ^{53}Mn [$(^{53}Mn/^{55}Mn)_0 = \sim 9 \times 10^{-6}$; e.g., Wasserburg et al. 2006].

Nucleosynthesis models for Type II supernovae predict $(^{60}Fe/^{56}Fe)_0$ for the solar system of from 3×10^{-7} to $>1 \times 10^{-5}$, depending on the mass and metallicity of the star, the nuclear reaction rates, and the kinetic energy of explosion (Wasserburg et al. 1998; Woosley & Weaver 1995; Rauscher et al. 2002; Chieffi & Limongi 2004). This is more than enough to produce the $(^{60}Fe/^{56}Fe)_0$ inferred from the chondrules. Current model calculations (Woosley & Weaver 1995; Chieffi & Limongi 2004; Meyer 2005) imply that a star with initial mass >25 $M_\odot$

and solar metallicity or a <25 $M_\odot$ star with a slightly low metallicity (~0.3–0.5 times the solar metallicity) that exploded ∼1 My before the solar system formed could explain abundances of ^{60}Fe as well as ^{26}Al and ^{41}Ca. However, the (^{53}Mn/^{55}Mn)$_0$ for the solar system inferred from models for Type II supernovae is 10–100 times larger than that estimated from meteorites. Meyer & Clayton (2000) and Meyer (2005) have explained this discrepancy by fallback of most of the ^{53}Mn onto a collapsing stellar core. ^{55}Mn is produced most efficiently in the innermost layer of the Type II supernova by Si burning. This indicates that a supernova with a less kinetic energy of explosion could be a source of short-lived radionuclides. While some of the ^{53}Mn could have come from the supernova, it is also possible that the ^{53}Mn represents primarily the steady state abundance in the interstellar medium (Jacobsen 2005; Wasserburg et al. 2006). ^{53}Mn may have formed energetic particle irradiation (e.g., Gounelle et al. 2001). Yet another possibility is that a Type II supernova shortly before the solar system formation may have contributed to only ^{53}Mn and ^{60}Fe and that the other short-lived radionuclides were brought from a nearby low-mass AGB star or were synthesized by energetic particle irradiation (Wasserburg et al. 2006). Although additional theoretical work is required, a supernova is currently the best option for the source that provided the stellar contribution of short-lived radionuclides to the early solar system.

If a supernova explosion near the newly forming solar system contributed to the inventory of short-lived radionuclides in the solar system, it constrains the environment where the Sun formed. Most stars form in massive molecular clouds where hundreds of stars with a wide range of masses form at approximately the same time (Lada & Lada 2003). Massive stars have short lifetimes and can explode as supernovae in only a few million years, strongly affecting the star-forming region around them. A long-standing idea is that the explosion of a supernova may have triggered the gravitational collapse of the solar system and may have injected supernova materials into the collapsing system (Cameron & Truran 1977). Alternatively, intense stellar winds of the presupernova massive star may have triggered the collapse of the solar system, after which the massive star exploded and injected newly synthesized material into the already-formed accretion disk (Hester et al. 2004; Hester & Desch 2005). Although we cannot currently say how a nearby supernova may have interacted with the early solar system, the high (^{60}Fe/^{56}Fe)$_0$ ratio inferred from chondrules gives a clear indication of such an interaction. This suggests that the solar system formed in a region where hundreds of stars were forming at once, much like the Orion Nebula is today, rather than in a region where low-mass stars form in near isolation, like in the Tauris-Auriga region.

Our results also provide an anchor point on which to construct an Fe-Ni chronology of the early solar system.

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REFERENCES

Alexander, C. M. O'D., Barber, D. J., & Hutchison, R. 1989, Geochim. Cosmochim. Acta, 53, 3045
Amelin, Y., Krot, A. N., Hutcheon, I. D., & Ulyanov, A. A. 2002, Science, 297, 1678
Arnould, M., Paulus, G., & Maynet, G. 1997, A&A, 321, 452
Birck, J. L., & Lugmair, G. W. 1988, Earth Planet. Sci. Lett., 90, 131
Cameron, A. G. W., & Truran, J. W. 1977, Icarus, 30, 447
Chieffi, A., & Limongi, M. 2004, ApJ, 608, 405
Choi, B.-G., Huss, G. R., & Wasserburg, G. J. 1999, Lunar Planet. Sci. Conf., 30, 1862
Condit, R. H., Hobbins, R. R., & Birchenall, C. E. 1974, Oxid. Metals, 8, 409
Ganguly, J., & Tazzoli, V. 1994, Am. Mineral., 79, 930
Gounelle, M., Shu F. H., Shang, H., Glassgold, A. E., Rehm, K. E., & Lee T. 2001, ApJ, 548, 1051
Grossman, J. N., & Brearley, A. J. 2005, Meteoritics Planet. Sci., 40, 87
Guan, Y., Huss, G. R., & Leshin, L. A. 2004, Appl. Surf. Sci., 231-232, 899
Hester, J. J., & Desch, S. J. 2005, in ASP Conf. Ser. 341, Chondrites and the Protoplanetary Disk, ed. A. N. Krot, E. R. D. Scott, & B. Reipurth (San Francisco: ASP), 107
Hester, J. J., Desch, S. J., Healy, K. R., & Leshin, L. A. 2004, Science, 304, 1116
Huss, G. R., & Lewis, R. S. 1994, Meteoritics, 29, 811
Huss, G. R., & Tachibana, S. 2004, Lunar Planet. Sci. Conf., 35, 1811
Jacobsen S. 2005, in ASP Conf. Ser. 341, Chondrites and the Protoplanetary Disk, ed. A. N. Krot, E. R. D. Scott, & B. Reipurth (San Francisco: ASP), 548
Jarosewich, E. 1990, Meteoritics, 25, 323
Kastner, J. H., & Meyers P. C. 1994, ApJ, 421, 605
Kita, N. T., Huss, G. R., Tachibana, S., Amelin, Y., Nyquist, L. E., & Hutcheon, I. D. 2005a, in ASP Conf. Ser. 341, Chondrites and the Protoplanetary Disk, ed. A. N. Krot, E. R. D. Scott, & B. Reipurth (San Francisco: ASP), 558
Kita, N. T., Nagahara, H., Togashi, S., & Morishita, Y. 2000, Geochim. Cosmochim. Acta, 64, 3913
Kita, N. T., Togashi, S., Morishita, Y., Terashima, S. & Yurimoto, H. 1998, Antarctic Meteorite Res., 11, 103
Kita, N. T., Tomomura, S., Tachibana, S., Nagahara, H., Mostefaoui, S., & Morishita, Y. 2005b, Lunar Planet. Sci. Conf., 36, 1750
Krot, A. N., et al. 1997, Geochim. Cosmochim. Acta, 61, 219
Lada, C. J., & Lada, E. 2003, ARA&A, 41, 57
Lauretta, D. S. 2005, Oxid. Metals, 64, 1
McKeegan, K. D., Chaussidon, M., & Robert, F. 2000, Science, 289, 1334
Meyer, B. S. 2005, in ASP Conf. Ser. 341, Chondrites and the Protoplanetary Disk, ed. A. N. Krot, E. R. D. Scott, & B. Reipurth (San Francisco: ASP), 515
Meyer, B. S., & Clayton, D. D. 2000, Space Sci. Rev., 92, 133
Mostefaoui, S., Kita, N. T., Togashi, S., Tachibana, S., Nagahara, H., & Morishita, Y. 2002, Meteoritics Planet. Sci., 37, 421
Mostefaoui, S., Lugmair, G. W., & Hoppe, P. 2005, ApJ, 625, 271
Rambaldi, E. R., & Wasson, J. T. 1981, Geochim. Cosmochim. Acta, 45, 1001
Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 323
Shukolyukov, A., & Lugmair, G. W. 1993, Science, 259, 1138
Tachibana, S., & Huss, G. R. 2003, ApJ, 588, L41
Wasserburg, G. J., Busso, M., & Gallino, R. 1996, ApJ, 466, L109
Wasserburg, G. J., Busso M., Gallino R., & Nollett K. M. 2006, Nucl. Phys. A, in press
Wasserburg, G. J., Busso, M., Gallino, R., & Raiteri, C. M. 1994, ApJ, 424, 412
Wasserburg, G. J., Gallino, R., & Busso, M. 1998, ApJ, 500, L189
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181