The Astrophysical Journal, 588:L41–L44, 2003 May 1

THE INITIAL ABUNDANCE OF ^{60}Fe IN THE SOLAR SYSTEM

S. Tachibana[1] and G. R. Huss[1,2]
Received 2003 February 17; accepted 2003 March 18; published 2003 March 31

ABSTRACT

^{60}Fe, which decays to radiogenic ^{60}Ni (^{60}Ni*), is a now extinct radionuclide. ^{60}Fe is produced only in stars and thus provides a constraint on the stellar contribution to solar system radionuclides. Its short half-life [$t_{1/2}$ = 1.49 × 10^6 yr (1.49 Myr)] makes it a potential chronometer for the early solar system. We found clear evidence for ^{60}Ni* in troilite (FeS) grains from the Bishunpur and Krymka chondrites, two of the least metamorphosed (LL3.1) ordinary chondrites. The weighted means of inferred initial ^{60}Fe/^{56}Fe ratios [(^{60}Fe/^{56}Fe)$_0$] for the troilites are (1.08 ± 0.23) × 10^{-7} and (1.73 ± 0.53) × 10^{-7} for Bishunpur and Krymka, respectively. We compare our data with upper limits established previously on (^{60}Fe/^{56}Fe)$_0$ for a chondrule in an unequilibrated ordinary chondrite, Semarkona, and for troilites in a relatively metamorphosed chondrite, Ste. Marguerite, taking into account their ^{26}Al-^{26}Mg ages. The ^{60}Fe and ^{26}Al chronometers can be combined to produce a consistent chronology for Ca-Al–rich inclusions, which are thought to be the earliest solar system solids, chondrules, troilites, and Ste. Marguerite. The initial ^{60}Fe/^{56}Fe for the solar system is inferred from this chronology to have been 2.8 × 10^{-7} to 4 × 10^{-7}. This is at or below the low end of predictions for a supernova source.

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

1. INTRODUCTION

The presence in the early solar system of several short-lived, now extinct, radionuclides (^{41}Ca, ^{26}Al, ^{10}Be, ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{182}Hf, and ^{129}I) has been confirmed through measurements of excesses of daughter isotopes that correlate with the abundances of their parent elements in cogenetic minerals in meteorites (Wasserburg & Papanastassiou 1982; Goswami & Vanhala 2000). These radionuclides provide high-resolution information on the timing of events in the earliest epochs of solar system history. Short-lived radionuclides were synthesized either by irradiation with energetic particles or by nucleosynthesis in stars. The recent discovery in Ca-Al–rich inclusions (CAIs) from carbonaceous chondrites of evidence for live ^{10}Be (McKeegan, Chaussidon, & Robert 2000), which is produced only by energetic-particle irradiation, has led to suggestions that the major portion of many short-lived radionuclides (^{41}Ca, ^{26}Al, ^{53}Mn, and ^{10}Be) was produced by irradiation (Gounelle et al. 2001). However, ^{60}Fe is not produced at all efficiently by particle irradiation (Lee et al. 1998; Clayton & Jin 1995), so its presence requires a stellar contribution to short-lived radionuclides. A reliable estimate for the initial abundance of ^{60}Fe in the solar system places constraints on the type of stellar source (Wasserburg et al. 1994; Wasserburg, Gallino, & Busso 1998).

The first hint of ^{60}Fe in the solar system was found as excesses of ^{60}Ni in CAIs (Birck & Lugmair 1988). These data can be interpreted to indicate an ^{60}Fe/^{56}Fe ratio at the time of CAI formation of (1.6 ± 0.5) × 10^{-6}. However, the measured ^{60}Ni excesses might reflect isotopically anomalous Ni from preexisting stellar condensates rather than decay of ^{60}Fe (Shukolyukov & Lugmair 1993a). The first clear evidence for ^{60}Fe was found in three eucrites, Chervony Kut, Juvinas, and Caldera, which are basaltic rocks produced by planetary-scale differentiation (Shukolyukov & Lugmair 1993a, 1993b, 1996). The inferred (^{60}Fe/^{56}Fe)$_0$ for Chervony Kut and Juvinas are significantly lower than that inferred for CAIs and differ considerably from one another: (3.9 ± 0.6) × 10^{-9} and (4.3 ± 1.5) × 10^{-10}, respectively. In contrast, the abundances of ^{53}Mn ($t_{1/2}$ = 3.7 Myr) inferred for those eucrites are quite similar [(^{53}Mn/^{55}Mn)$_0$ = (3.7 ± 0.4) × 10^{-6} for Chervony Kut and (3.0 ± 0.5) × 10^{-6} for Juvinas] (Lugmair & Shukolyukov 1998). The ^{53}Mn-^{53}Cr system is apparently more resistant to secondary disturbance than the ^{60}Fe-^{60}Ni system (Lugmair & Shukolyukov 1998). The spread in (^{60}Fe/^{56}Fe)$_0$ for eucrites indicates that the ^{60}Fe-^{60}Ni system does not date eucrite formation and thus cannot be used to estimate the initial ^{60}Fe abundance of the solar system.

Recently, several searches for evidence of ^{60}Fe have been made in chondrites, which did not totally melt and are more primitive than eucrites (Shukolyukov & Lugmair 1993b; Choi, Huss, & Wasserburg 1999; Kita et al. 2000). Troilite from a relatively metamorphosed chondrite, Ste. Marguerite, showed an unresolved hint of ^{60}Ni* and gave an upper limit of 2.4 × 10^{-8} for (^{60}Fe/^{56}Fe)$_0$ (Shukolyukov & Lugmair 1993b). Ion-microprobe studies of olivine phenocrysts in chondrules, submillimeter-sized once-molten spherules that are a major constituent of chondrites, gave no resolvable ^{60}Ni* in the unequilibrated ordinary chondrites Semarkona and Bishunpur (Kita et al. 2000; Choi et al. 1999). The upper limit for (^{60}Fe/^{56}Fe)$_0$ in a Semarkona chondrule was 1.4 × 10^{-7} (Kita et al. 2000), while that for Bishunpur and Semarkona chondrule olivines was 1.6 × 10^{-6} (Choi et al. 1999). Ion microprobe measurements of a sulfide-rich opaque inclusion and spinels within a CAI (Choi et al. 1999) revealed no resolvable ^{60}Ni*, and the upper limits on (^{60}Fe/^{56}Fe)$_0$ were 1.7 × 10^{-6} and 1.1 × 10^{-6} for sulfides and spinels, respectively.

In this work, we used the ion microprobe to study troilite (FeS), a ubiquitous mineral in chondrites, in two of the least metamorphosed ordinary chondrites, Bishunpur and Krymka (both LL3.1), to look for evidence for "live" ^{60}Fe.

2. EXPERIMENTAL PROCEDURES

About 190 troilite grains in thin sections of Bishunpur and Krymka were screened by scanning electron microscope to find grains with high Fe/Ni. Fe and Ni isotopic measurements were made for 10 selected troilites and associated metal from Bishunpur and three troilites from Krymka using the ASU Cameca

[1] Department of Geological Sciences, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404; tachi@asu.edu.

[2] Center for Meteorite Studies, Arizona State University, P.O. Box 872504, Tempe, AZ 85287-2504; gary.huss@asu.edu.

TABLE 1
Fe-Ni Isotope Data for Troilite Grains

Mineral (1)	^{56}Fe/^{61}Ni (×10^4) (2)	δ^{60}Ni (‰) (3)	^{60}Ni/^{61}Ni (4)	Correlation Coefficient (5)
Bishunpur 2359-6-TR41				
M	0.142 ± 0.016	−1.2 ± 4.3	23.07 ± 0.10	0.88
M	0.152 ± 0.018	−0.6 ± 6.0	23.09 ± 0.14	0.88
M	0.193 ± 0.022	2.4 ± 4.1	23.16 ± 0.09	0.88
Tr	4.21 ± 0.20	2.2 ± 3.5	23.15 ± 0.08	0.87
Tr	13.3 ± 0.7	1.6 ± 8.0	23.14 ± 0.19	0.88
Tr	479 ± 19	30 ± 19	23.79 ± 0.44	0.89
Tr	573 ± 23	31 ± 40	23.81 ± 0.93	0.89
Tr	628 ± 24	29 ± 15	23.77 ± 0.36	0.89
Tr	652 ± 26	63 ± 23	24.55 ± 0.54	0.89
Tr	702 ± 27	11 ± 23	23.36 ± 0.53	0.89
Tr	778 ± 30	34 ± 20	23.87 ± 0.46	0.89
Bishunpur 2359-6-TR2				
M	0.119 ± 0.005	−0.9 ± 2.0	23.08 ± 0.05	0.80
Tr	26.8 ± 3.0	0.9 ± 6.7	23.12 ± 0.15	0.89
Tr	55.9 ± 3.8	0.5 ± 5.1	23.11 ± 0.12	0.89
Tr	87.6 ± 6.0	9.1 ± 8.0	23.31 ± 0.19	0.89
Tr	362 ± 17	14 ± 11	23.43 ± 0.25	0.89
Bishunpur 2359-6-TR47				
M	0.142 ± 0.005	−0.2 ± 2.2	23.10 ± 0.05	0.81
Tr	12.8 ± 1.6	0.05 ± 6.1	23.10 ± 0.14	0.81
Tr	29.8 ± 2.7	2.0 ± 7.9	23.15 ± 0.18	0.89
Tr	82.9 ± 10.6	1.6 ± 10	23.14 ± 0.23	0.89
Tr	125 ± 15	−7.4 ± 14.7	22.93 ± 0.34	0.89
Tr	204 ± 12	8.6 ± 8.9	23.30 ± 0.21	0.89
Tr	283 ± 31	23 ± 12	23.64 ± 0.27	0.89
Tr	305 ± 33	15 ± 26	23.44 ± 0.59	0.89
Krymka 1729-3-TR1				
M	0.133 ± 0.007	−0.5 ± 3.0	23.09 ± 0.07	0.79
Tr[a]	182 ± 13	13 ± 15	23.41 ± 0.35	0.89
Tr	212 ± 13	13 ± 16	23.40 ± 0.37	0.89
Tr	406 ± 29	46 ± 34	24.17 ± 0.79	0.89
Tr	1104 ± 63	81 ± 50	24.98 ± 1.16	0.88
Krymka 1729-3-TR12				
Tr	3.83 ± 0.36	−0.2 ± 5.0	23.10 ± 0.12	0.88
Tr	42.9 ± 4.2	0.4 ± 17	23.11 ± 0.39	0.89
Tr	1590 ± 157	113 ± 63	25.71 ± 1.45	0.89

Note.—All errors are 2 σ. Col. (1): M = metal, Tr = troilite. Col. (3): Excesses of ^{60}Ni are expressed by δ^{60}Ni (‰) = Δ^{60}Ni − ($-\Delta^{62}$Ni), where Δ^{m}Ni (‰) = $\{[(^{m}\mathrm{Ni}/^{61}\mathrm{Ni})_{\mathrm{sample}}/(^{m}\mathrm{Ni}/^{61}\mathrm{Ni})_{\mathrm{normal}}] - 1\} \times 1000$ (m = 60, 62). The $(^{m}\mathrm{Ni}/^{61}\mathrm{Ni})_{\mathrm{normal}}$ are 23.100 for m = 60 and 3.1760 for m = 62 (Birck & Lugmair 1988). Col. (4): The corrected ^{60}Ni/^{61}Ni ratios are calculated by applying δ^{60}Ni to the literature value of 23.100. Col. (5): A correlation coefficient shows the linear correlation between errors on ^{57}Fe/^{61}Ni and ^{60}Ni/^{61}Ni.

[a] Troilite inside chondrule surrounded by troilite 1729-3-TR12.

ims-6f ion microprobe. A 3–4 nA O$^-$ primary beam was accelerated to 12.5 kV and focused to a 10–20 μm spot. The secondary accelerating voltage and energy window were 8.85 kV and 50 eV, respectively. A 400 μm contrast aperture and a 75 μm image field were used. The mass resolving power was 4500, which is sufficient to resolve most molecular interferences but cannot resolve hydride interferences on ^{57}Fe, ^{61}Ni, and ^{62}Ni peaks. However, the contributions of hydrides were negligibly small (less than 0.1 ‰). Secondary ^{57}Fe$^+$, ^{60}Ni$^+$, ^{61}Ni$^+$, and ^{62}Ni$^+$ ions were counted on the electron multiplier for 1, 10, 30, and 10 s in each cycle, respectively. ^{58}Ni and ^{64}Ni were not measured because of isobaric interferences from ^{58}Fe and ^{64}Zn, respectively. The count rate for ^{56}Fe was too high for the electron multiplier. The measured ^{57}Fe/^{61}Ni was converted to ^{56}Fe/^{61}Ni using ^{57}Fe/^{56}Fe = 0.023261 (Völkening & Papanastassiou 1989). Sensitivity factors for the Fe/Ni elemental ratios of troilite and metal were determined using terrestrial pyrrhotite and stainless steel. The instrumental mass fractionation for ^{60}Ni/^{61}Ni was corrected internally using the measured ^{62}Ni/^{61}Ni. Our error analysis takes into account the correlated component introduced by the large uncertainty on ^{61}Ni (York 1969).

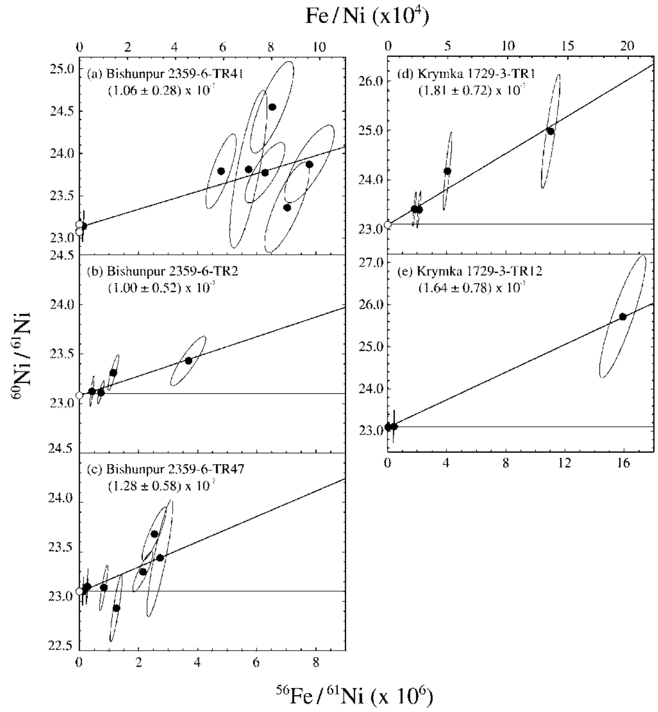

Fig. 1.—^{60}Fe-^{60}Ni isotopic systematics for five individual troilite grains (*filled circles*) and associated metal (*open circles*). Metal grains plot on the y-axis. The 2 σ uncertainty for each data point is shown as an error ellipse, which accounts for the correlated component that comes from the error on ^{61}Ni. The solid lines are error-weighted least-squares fits through the data, and the slopes with 2 σ uncertainties are given. Since $(^{60}\mathrm{Ni}/^{61}\mathrm{Ni})_{\mathrm{meas}} = (^{60}\mathrm{Ni}/^{61}\mathrm{Ni})_0 + (^{60}\mathrm{Ni}^*/^{61}\mathrm{Ni}) = (^{60}\mathrm{Ni}/^{61}\mathrm{Ni})_0 + (^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0 \times (^{56}\mathrm{Fe}/^{61}\mathrm{Ni})$, the slope of the fitting line gives the initial ratio $[(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0]$, the ratio at the time the ^{60}Fe-^{60}Ni system closed. Scales for both ^{56}Fe/^{61}Ni and Fe/Ni are shown.

3. RESULTS

In Bishunpur, three troilites showed clear evidence for ^{60}Fe. Troilite 2359-6-TR41 (∼70 × 60 μm) is located between two chondrules and includes a couple of kamacite grains. The measured Fe/Ni ratio varied from 1700 to ∼1 × 10^5 across the troilite and sometimes changed during the measurement as the ion beam sputtered through regions of different Ni content. The highest Fe/Ni ratio is 6 times larger than the maximum Fe/Ni ratio found in CAI sulfides and 20–25 times larger than the ratios in chondrule olivines (Choi et al. 1999; Kita et al. 2000). Troilite 2359-6-TR41 exhibits resolved ^{60}Ni* (Table 1; Fig. 1*a*). An error-weighted least-squares regression through the data for coexisting metal and troilite, taking account of the correlated component of the errors, gives $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0 = (1.06 \pm 0.28) \times 10^{-7}$.

Troilite 2359-6-TR2 is an opaque assemblage (∼250 × 180 μm) consisting of troilite and kamacite at the rim of a high-FeO chondrule. It contains inclusions of chromite and Fe-rich olivine. Troilite 2359-6-TR2 also shows resolved ^{60}Ni*, which correlates with the Fe/Ni ratio (Table 1; Fig. 1*b*), and the inferred $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0$ is $(1.00 \pm 0.52) \times 10^{-7}$. Troilite 2359-6-TR47 (∼70 × 60 μm) is irregularly shaped and contains pyroxene inclusions. It is associated with kamacite in matrix. It also shows $^{60}Ni^*$, and its $(^{60}Fe/^{56}Fe)_0$ is $(1.28 \pm 0.58) \times 10^{-7}$ (Table 1; Fig. 1*c*).

The initial ratios for these three grains are statistically indistinguishable, and the weighted mean is $(1.08 \pm 0.23) \times 10^{-7}$, much larger than the ratios obtained in eucrites (Shukolyukov & Lugmair 1993a, 1993b, 1996).

Two troilites from Krymka show clearly resolved $^{60}Ni^*$. Troilite 1729-3-TR1 is the sulfide rim ($\sim 220 \times 120$ μm) on a FeO-rich olivine-pyroxene chondrule. It includes a few small metal grains (<20 μm). Excess ^{60}Ni is also observed in a $\sim$20 μm troilite inside the chondrule (Table 1). The least-squares fit of data for 1729-3-TR1 and the small troilite gives an $(^{60}Fe/^{56}Fe)_0$ of $(1.81 \times 0.72) \times 10^{-7}$ (Fig. 1*d*).

The S-shaped troilite 1729-3-TR12 ($\sim 400 \times 60$ μm) is located at the rim of compound olivine-rich chondrules. This troilite has the highest Fe/Ni ratio, 2.3×10^5, of the measured troilites. However, the extremely Ni-poor area is too limited for us to measure enough points for an internal isochron. The inferred $(^{60}Fe/^{56}Fe)_0$ from our limited data is $(1.64 \pm 0.78) \times 10^{-7}$. The weighted mean of $(^{60}Fe/^{56}Fe)_0$ for Krymka troilites, $(1.73 \pm 0.53) \times 10^{-7}$, is larger than that for Bishunpur troilites.

4. DISCUSSION

4.1. *Interpretation of* ^{60}Ni *Excess in Troilites*

Isochron diagrams such as Figure 1 can be rigorously constructed only if the metal and troilite formed together from an isotopically homogeneous reservoir and have remained undisturbed since formation. Bishunpur and Krymka (both LL3.1) experienced mild heating on the parent body (e.g., Huss & Lewis 1994, 1995). Thus, the metal-troilite assemblages may not fulfill the conditions for an isochron. The estimated temperature for Bishunpur metamorphism is less than 300°C (Rambaldi & Wasson 1981). Experimental data for vacancy diffusion suggest that Fe^{2+} can diffuse in pyrrhotite ($Fe_{0.997}S$) $\sim$1 cm in 10^5 yr at 277°C (Condit, Hobbins, & Birchenall 1974). Ni may diffuse at a similar rate in sulfide. However, Fe and Ni diffusion is less rapid in metal (e.g., Sparke, James, & Leak 1965). Thus, while the ^{60}Fe-^{60}Ni system in troilites may have been disturbed or reset by mild parent-body metamorphism, it is not likely to have been reset in metal. In any case, addition of $^{60}Ni^*$ to metal would not produce a detectable shift in $^{60}Ni/^{61}Ni$ because of the high Ni content of the metal. The Ni isotopic composition of the metal is, therefore, considered to be a reasonable substitute for the initial $^{60}Ni/^{61}Ni$ of the system, and "isochrons" constructed through the troilite and metal data may give chronological information.

If Fe and Ni are mobile in troilite at 300°C, as diffusion data imply, and the ^{60}Fe-^{60}Ni system was reset on the parent body, the isochrons could plausibly date parent-body metamorphism. However, the diffusion rates may actually be slower in troilite than in pyrrhotite because of fewer vacancies in troilite. If so, the isochrons might date troilite formation. Data for Krymka 1729-3-TR1 cluster tightly around a single isochron (although with relatively large measurement errors), implying an undisturbed isotope system (Fig. 1*d*). In contrast, data for Bishunpur 2359-6-TR41 scatter around the isochron more than might be expected from measurement errors (Fig. 1*a*). The inferred initial ratios for Kyrmka troilites are somewhat higher than those for Bishunpur troilites. If the two sets of troilite formed from the same isotopic reservoir, one can infer that Krymka troilites reflect formation from that reservoir and Bishunpur troilites have been somewhat disturbed by a thermal event occurring after ^{60}Fe had largely decayed. Taken at face value, the difference in $(^{60}Fe/^{56}Fe)_0$ between troilites in Bishunpur and Krymka implies a time difference of $\sim$1 Myr. However, if the Bishunpur troilites were not fully reset by the later thermal event, restarting the clock, then the inferred time difference is not meaningful, because redistribution could have taken place any time after the ^{60}Fe had decayed.

4.2. *Initial Abundance of* ^{60}Fe *in the Solar System*

The initial abundance of ^{60}Fe can help to constrain the stellar contribution to the short-lived radionuclides in the solar system. The upper limit on previous estimates of the initial $^{60}Fe/^{56}Fe$ of the solar system is $(1.6 \pm 0.5) \times 10^{-6}$, based on ^{60}Ni excesses in CAIs (Birck & Lugmair 1988). Lower limits of $\sim 1.2 \times 10^{-8}$ to $\sim 1.2 \times 10^{-7}$ can be calculated from the $(^{60}Fe/^{56}Fe)_0$ ratio in the Chervony Kut eucrite $[(3.9 \pm 0.6) \times 10^{-9}]$ by assuming CAI-eucrite time intervals of 2.4–7.4 Myr based on the ^{53}Mn-^{53}Cr system (Shukolyukov & Lugmair 1993b; Lugmair & Shukolyukov 1998).

Our new data significantly reduce the possible range for the solar system initial ratio, assuming that the measured ratios reflect the average solar system abundance. The measured $(^{60}Fe/^{56}Fe)_0$ for Krymka troilites, $(1.73 \pm 0.53) \times 10^{-7}$, provides a strict lower limit of 1.2×10^{-7} on the initial $^{60}Fe/^{56}Fe$ in the solar system. This assumes that the troilite and the solar system formed at the same time. The upper limit and a best estimate for the initial ratio can be inferred by building on the chronology established by other short-lived radionuclides. Figure 1*d* shows data for troilites occurring both as the rim on a chondrule and as a grain within that chondrule. Troilite can be a primary mineral within chondrules, it can condense as rims on chondrules, or it can form by sulfidization of metal after the chondrule formed (Rubin, Saylor, & Wasson, 1999; Lauretta, Buseck, & Zega, 2001). We do not have clear evidence for the mode of origin of the Krymka troilite, but it appears to have formed prior to parent-body accretion. If the troilite formed at the same time as the chondrule or very shortly thereafter, chondrule chronology can be used to place the troilites in time.

Chondrules appear to have formed 1–3 Myr after CAIs (Kita et al. 2000; Huss et al. 2001; Mostefaoui et al. 2002). The Semarkona (LL3.0) chondrule, CH4, which ^{26}Al chonology indicates formed 1.7 ± 0.2 Myr after CAIs, gave an upper limit on $(^{60}Fe/^{56}Fe)_0$ of less than 1.4×10^{-7} (Kita et al. 2000). This is essentially equivalent to our measured values for Krymka. Assuming a time delay of 1–2 Myr between CAI and chondrule formation, our measured $(^{60}Fe/^{56}Fe)_0$ ratio of $(1.73 \pm 0.53) \times 10^{-7}$ implies an initial ratio for the solar system in the range of 1.9×10^{-7} to 5.7×10^{-7}, with the most probable range of 2.8×10^{-7} to 4.5×10^{-7}. An alternative calculation can be done using data for the H4 chondrite, Ste. Marguerite. The upper limit on $(^{60}Fe/^{56}Fe)_0$ obtained for troilite in Ste. Marguerite, less than 2.4×10^{-8} (Shukolyukov & Lugmair 1993b), implies a time delay of greater than 4.2 Myr after the event recorded in Krymka troilite or greater than 5.2 Myr to greater than 6.2 Myr after CAIs. This time interval is broadly consistent with the 5.4 ± 0.1 Myr interval estimated from ^{26}Al-^{26}Mg systematics (Zinner & Göpel 2002) but suggests that the interval between CAIs and Krymka troilites is closer to 1 than 2 Myr. This would decrease the upper limit for the initial $^{60}Fe/^{56}Fe$ ratio to less than 4.5×10^{-7}, perhaps as low as 3.2×10^{-7}. Thus, ^{60}Fe-^{60}Ni and ^{26}Al-^{26}Mg data for Krymka troilite, chondrule CH4, and Ste. Marguerite seem to provide a coherent chronology (Fig. 2), which lends confidence to our estimate of the solar system initial ratio.

From the preceding considerations, we can place strong con-

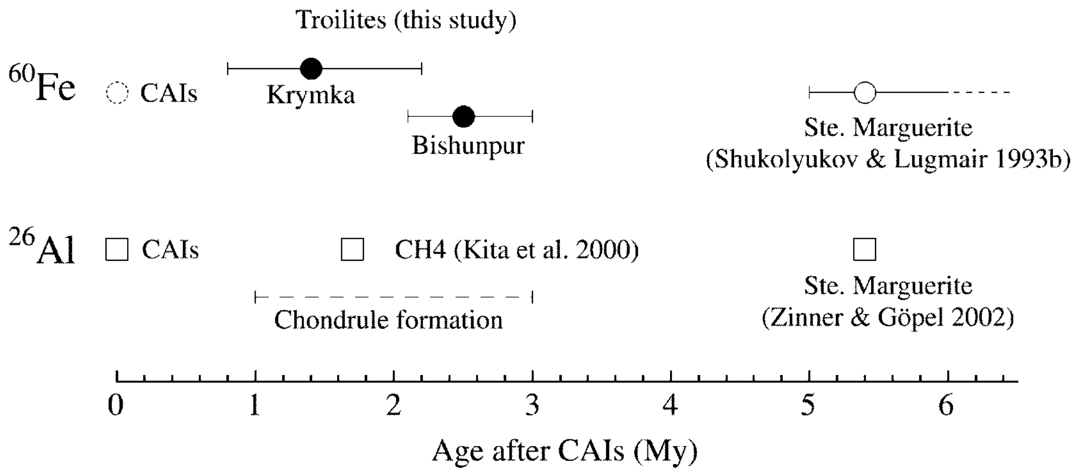

FIG. 2.—Comparison between ^{26}Al and ^{60}Fe chronologies of early solar system objects. The ^{26}Al ages after CAIs of Semarkona chondrule, CH4, and Ste. Marguerite (*open squares*) and the probable duration for chondrule formation are shown. The ^{60}Fe ages of toilites (*filled circles*) and Ste. Marguerite (*open circle*) are evaluated using the ^{26}Al age of CH4 (1.7 ± 0.2 Myr) as an anchor.

straints on the value for ^{60}Fe/^{56}Fe when the solar system formed of between 1.2×10^{-7} (lower limit on our measured value) and 5.7×10^{-7}, with a most probable value between 2.8×10^{-7} and 4×10^{-7}.

4.3. *Possible Sources of* ^{60}Fe *in the Early Solar System*

The range of ^{60}Fe/^{56}Fe at the time of the solar system formation inferred in this study is larger than the steady-state ratio for the interstellar medium (~2.6×10^{-8}; Wasserburg, Busso, & Gallino 1996). Additional production of ^{60}Fe in or near the solar system shortly before or during solar system formation is required. Because ^{60}Fe is not produced at all efficiently by particle irradiation (Lee et al. 1998; Clayton & Jin 1995), a stellar source is implied. A supernova (SN) explosion, which might have triggered solar system formation, could potentially provide the short-lived radionuclides. Wasserburg et al. (1998) showed that because both ^{26}Al and ^{60}Fe are produced dominantly in the O/Ne zone of the pre-SN star, the two nuclei should be correlated in the SN ejecta regardless of the details of mixing, shredding, or the nature of the injection into the solar nebula. Using the inferred $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ for the early solar system, these authors predict a range for ^{60}Fe/^{56}Fe of 3.2×10^{-7} to 1.3×10^{-5}. The initial ^{60}Fe/^{56}Fe ratio inferred from our data for the early solar system is at or below the low end of this range. An asymptotic giant branch star could also be a source of short-lived nuclides. However, current models do not produce ^{60}Fe efficiently, and the initial ^{60}Fe/^{56}Fe that we infer could be produced only under extremely neutron-rich conditions (Wasserburg et al. 1994). Nonexploding Wolf-Rayet stars cannot produce the estimated initial ^{60}Fe/^{56}Fe ratio at all (Arnould, Paulus, & Meynet 1997). Improved models of various stellar sources will be required to determine the source of ^{60}Fe in the solar system.

We thank G. MacPherson of the Smithsonian Institution, S. Russell of the British Museum, and G. Kurat of the Natural History Museum, Vienna, for loans of Bishunpur and Krymka thin sections. G. Lugmair and N. Kita provided valuable suggestions, and F. Mazdab and R. Hervig supplied the terrestrial pyrrhotite. We are supported by NASA grant NAG5-11543 (G. R. H.) and a Japan Society for the Promotion of Science Research Fellowship for Young Scientists (S. T.).

REFERENCES

Arnould, M., Paulus, G., & Meynet, G. 1997, A&A, 321, 452
Birck, J. L., & Lugmair, G. W. 1988, Earth Planet. Sci. Lett., 90, 131
Choi, B.-G., Huss, G. R., & Wasserburg, G. J. 1999, Lunar Planet. Sci. Conf., 30, 1862
Clayton, D. D., & Jin, L. 1995, ApJ, 451, 681
Condit, R. H., Hobbins, R. R., & Birchenall, C. E. 1974, Oxid. Metals, 8, 409
Goswami, J. N., & Vanhala, H. A. T. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 963
Gounelle, M., Shu, F. H., Shang, H., Glassgold, A. E., Rehm, K. E., & Lee, T. 2001, ApJ, 548, 1051
Huss, G. R., & Lewis, R. S. 1994, Meteoritics, 29, 811
———. 1995, Geochim. Cosmochim. Acta, 59, 115
Huss, G. R., MacPherson, G. J., Wasserburg, G. J., Russell, S. S., & Srinivasan, G. 2001, Meteoritics Planet. Sci., 36, 975
Kita, N. T., Nagahara, H., Togashi, S., & Morishita, Y. 2000, Geochim. Cosmochim. Acta, 64, 3913
Lauretta, D. S., Buseck, P. R., & Zega, T. 2001, Geochim. Cosmochim. Acta, 65, 1337
Lee, T., Shu, F. H., Shang, H., Glassgold, A. E., & Rehm, K. E. 1998, ApJ, 506, 898
Lugmair, G. W., & Shukolyukov, A. 1998, Geochim. Cosmochim. Acta, 62, 2863
McKeegan, K. D., Chaussidon, M., & Robert, F. 2000, Science, 289, 1334
Mostefaoui, S., Kita, N. T., Togashi, S., Tachibana, S., Nagahara, H., & Morishita, Y. 2002, Meteoritics Planet. Sci., 37, 421
Rambaldi, E. R., & Wasson, J. T. 1981, Geochim. Cosmochim. Acta, 45, 1001
Rubin, A. E., Saylor, A. L., & Wasson, J. T. 1999, Geochim. Cosmochim. Acta, 63, 2281
Shukolyukov, A., & Lugmair, G. W. 1993a, Science, 259, 1138
———. 1993b, Earth Planet. Sci. Lett., 119, 159
———. 1996, Meteoritics Planet. Sci., 31, A129
Sparke, B., James, D. W., & Leak, G. M. 1965, J. Iron Steel Inst., 203, 152
Völkening, J., & Papanastassiou, D. A. 1989, ApJ, 347, L43
Wasserburg, G. J., Busso, M., & Gallino, R. 1996, ApJ, 466, L109
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
Wasserburg, G. J., & Papanastassiou, D. A. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton, D. N. Schramm, & W. A. Fowler (New York: Cambridge Univ. Press), 77
York, D. 1969, Earth Planet. Sci. Lett., 5, 320
Zinner, E., & Göpel, C. 2002, Meteoritics Planet. Sci., 37, 1001