

^{60}Fe : A HEAT SOURCE FOR PLANETARY DIFFERENTIATION FROM A NEARBY SUPERNOVA EXPLOSION

S. MOSTEFAOUI,¹ G. W. LUGMAIR,^{1,2} AND P. HOPPE¹

Received 2004 November 3; accepted 2005 February 1

ABSTRACT

From a sample of the Semarkona (LL 3.0) ordinary chondrite we report the in situ discovery of ^{60}Ni isotopic anomalies attributable to the decay of short-lived ^{60}Fe (half-life 1.5 Myr) in the mineral phases troilite (FeS) and magnetite (Fe_3O_4). The troilite shows a ^{60}Ni excesses of up to ~ 100 parts per thousand (‰) relative to its solar isotopic abundance. A positive correlation between ^{60}Ni excesses and $^{56}\text{Fe}/^{58}\text{Ni}$ ratios provides evidence for live ^{60}Fe in the early solar system. The inferred $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $(0.92 \pm 0.24) \times 10^{-6}$ is the highest measured in any meteorite sample so far. This ratio is higher than predictions for production within asymptotic giant branch stars, but falls within the range expected for a Type II supernova source. This result is strongly suggestive of injection of freshly synthesized ^{60}Fe into the nascent solar nebula by a nearby supernova explosion. Such a high abundance of ^{60}Fe will exclude irradiation with solar energetic particles as the sole mechanism responsible for the production of short-lived radionuclides. It further shows that the decay of ^{60}Fe was an important heat source for early planetary melting and differentiation and for keeping asteroids thermally active for much longer than would be possible from the decay of ^{26}Al alone.

Subject headings: dust, extinction — nuclear reactions, nucleosynthesis, abundances — solar system: formation — supernovae: general

1. INTRODUCTION

Since the discovery of isotopic anomalies in meteorites in 1960 (Reynolds 1960), extensive efforts have been devoted to the study of the nucleosynthetic history of the materials that contributed to the formation of the solar system. This includes the production of nuclides in and around stars, their travel in the interstellar medium, and their subsequent incorporation into solid objects in the solar system. Meteorites provide the oldest matter formed in the solar system that we have access to. Their study reveals evidence for the existence and decay of short-lived, now extinct, radionuclides through the detection of anomalies in their daughter isotopes. These radionuclides were either synthesized by irradiation with energetic particles from the early Sun or are nucleosynthetic products from stars.

The nucleosynthetic production of short-lived radionuclides and their rapid injection into the nascent solar system can be used to put constraints on the timescale of events and processes that occurred at the early stages of solar system formation. Chronometers based on short-lived nuclides, such as ^{26}Al , ^{53}Mn , ^{60}Fe , ^{107}Pd , ^{129}I , and ^{146}Sm , were extensively studied during the last decades (Lee et al. 1976; Kelly & Wasserburg 1978; Lugmair et al. 1983; Birck & Allegre 1985; Swindle et al. 1988; Shukolyukov & Lugmair 1993). The radioactive decay of some of these short-lived radionuclides has long been considered as a potential heat source for planetary melting and differentiation (Urey 1955; Lee et al. 1976; Hutcheon & Hutchison 1989; Shukolyukov & Lugmair 1993). In particular, the heating of planetesimals by the decay of ^{26}Al (to ^{26}Mg) and ^{60}Fe (to ^{60}Ni) has recently been discussed (Yoshino et al. 2003), and quantitative models have been developed.

Whereas the relative amount of ^{26}Al (half-life ~ 0.7 Myr) in the early solar system, inferred from meteorite data, has long been considered sufficient as a significant heat source, the existence of ^{60}Fe (half-life ~ 1.5 Myr; Kutschera et al. 1984) was only discovered a decade ago (Shukolyukov & Lugmair 1993). However, it was unclear whether its abundance was sufficiently high to participate significantly in the heating of small planetary bodies. Both asymptotic giant branch (AGB) stars and supernovae (SNe) are expected to produce and expel ^{60}Fe . The amount of ^{60}Fe and the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio in SN ejecta are predicted to be distinctly higher than in the winds of AGB stars (Wasserburg et al. 1998). The former existence of ^{60}Fe at relatively high abundance within meteorites would serve as evidence for a supernova explosion in close proximity to the solar system during its birth. In an attempt to help answer these questions we report new results on ^{60}Ni isotopic anomalies in troilite (FeS) and magnetite (Fe_3O_4) from the primitive meteorite Semarkona (LL 3.0).

2. EXPERIMENTAL METHODS

The in situ Fe and Ni isotopic measurements were performed with the CAMECA NanoSIMS-50 ion microprobe. The NanoSIMS is a new generation secondary ion mass spectrometer, installed three years ago at the Max-Planck-Institute for Chemistry at Mainz. It is characterized by high spatial resolution (down to 50 nm), high sensitivity, and the capability of simultaneous detection of up to six isotopes. In this study, positive secondary ions of ^{54}Fe , ^{60}Ni , and ^{62}Ni , produced by bombardment of our samples with an ~ 0.5 – 1 nA O^- beam of ~ 5 μm in size, were measured in multidetection mode at a mass resolution of $m/\Delta m \sim 2500$ (^{54}Fe) and ~ 3500 – 4500 (^{60}Ni and ^{62}Ni), sufficient to separate isobaric interferences from compounds such as $^{30}\text{Si}_2$, ^{44}CaO , and ^{46}TiO . However, for ^{62}Ni , despite its peak-to-peak resolution from ^{46}TiO , we found that the tail of ^{46}TiO can contribute to the ^{62}Ni signal, where its contribution becomes a serious problem in troilite grains with low Ni content. We verified this by measuring ilmenite (FeTiO_3) grains with very low Ni contents.

¹ Max-Planck-Institut für Chemie (Otto-Hahn-Institut), Becherweg 27, D-55128 Mainz, Germany; smail@mpch-mainz.mpg.de.

² Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0212.

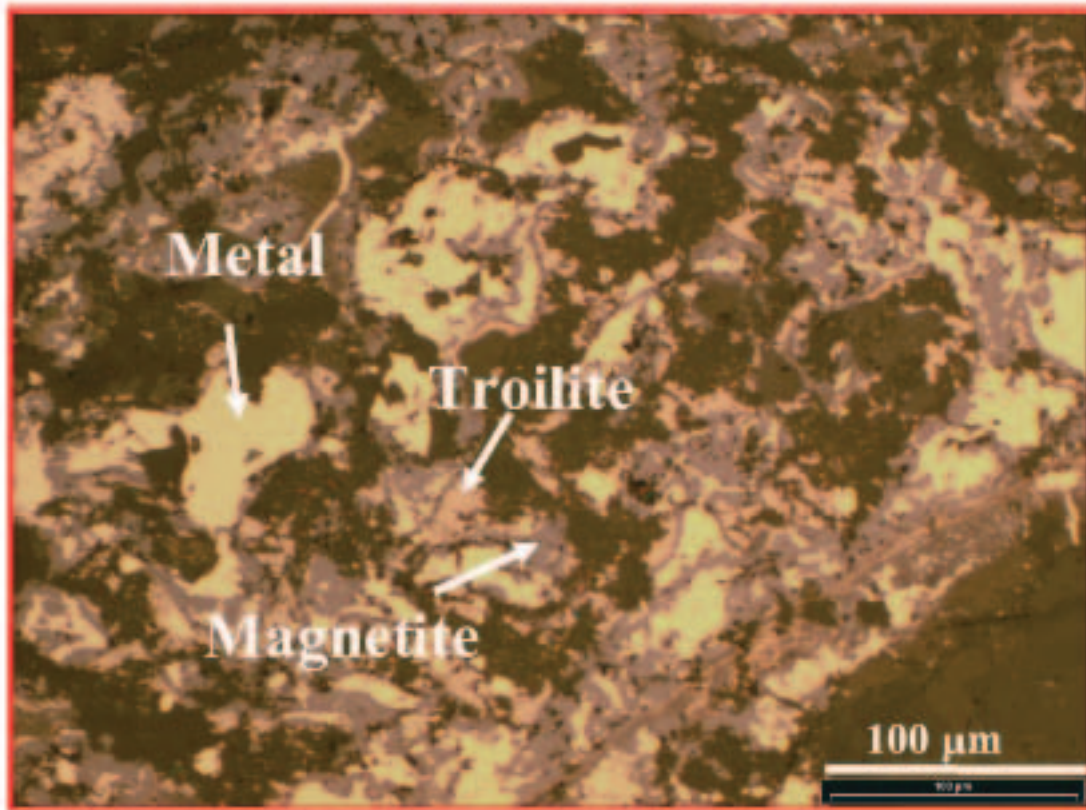


Fig. 1.—Optical microscope image of a troilite-metal-magnetite assemblage in the Semarkona chondrite. The scale bar is 100 μm .

Up to 90% of the signal was found to come from the tail of ^{46}TiO . To avoid this problem we only studied in detail troilite grains that were first verified to exhibit no ^{46}TiO interference. A ^{59}CoH interference, which is not fully resolved from ^{60}Ni , was shown to be negligible (<1 part per thousand [‰] of ^{60}Ni signal) in all samples of this study. The dynamic background was measured by detuning the voltages of the deflection plates in front of the electron multipliers by -12 V (corresponding to $\Delta m = -30$ mamu from the peak center) for each mass. Contributions from the dynamic background (<0.01 counts s^{-1}) to the ^{60}Ni and ^{62}Ni secondary ion signals (typically 35 counts s^{-1} and 5 counts s^{-1} , respectively) were low. The $^{56}\text{Fe}/^{58}\text{Ni}$ ratio was calculated from the measured $^{54}\text{Fe}/^{62}\text{Ni}$ secondary ion ratio divided by the relative Fe/Ni sensitivity factor. The latter was determined on a synthetic FeS standard with known Fe/Ni ratio (bulk Fe/Ni = 640). Microscopic heterogeneities in the Fe/Ni ratio of this standard caused a systematic uncertainty of approximately $\pm 20\%$ (2σ) in the $^{56}\text{Fe}/^{58}\text{Ni}$ ratio for each of our measurement sessions. The instrumental mass fractionation for $^{60}\text{Ni}/^{62}\text{Ni}$ ratios was corrected using Ni-rich phases found in the vicinity of the selected Semarkona troilites. In order to quantify matrix effects, we measured various standard minerals including Fe-Ni alloy, St. Carlos olivine, and NIST SRM611 glass under the same analytical conditions. Uncertainties in $^{60}\text{Ni}/^{62}\text{Ni}$ due to the matrix effects were thus quantified to be about $\pm 5\%$. Alternatively, ^{61}Ni could have been measured to facilitate the internal mass fractionation correction. However, because of the lower abundance of ^{61}Ni and collector restrictions, at least double the measurement time would be needed to achieve adequate precision. In this combined multi-/single collector mode we found that in addition to cratering effects due to the long sputtering time, Ni-poor troilite sputters away during the measurement. In contrast,

in multidetection mode cratering effect problems could be minimized by not exceeding measurement times of ~ 1 hr. In order to exclude problems related to instrumental mistuning or unexpected compositional effects, synthetic sulfides (FeS, FeS_2 , Fe_7S_8), covering the whole range of Fe/Ni ratios of the Semarkona troilite compositions, were measured under the same analytical conditions as for the Semarkona troilites.

3. RESULTS

3.1. Petrography

Semarkona (LL3.0) is a very primitive ordinary chondrite, where the disturbance of the ^{60}Fe - ^{60}Ni radiogenic system during parent body processing is expected to be minimal, a prerequisite for a reliable estimate of the initial solar system ^{60}Fe abundance. We examined the minerals troilite (FeS) and magnetite (Fe_3O_4) using optical and scanning electron microscopy (SEM) and an electron microprobe (EMPA). We were able to clearly distinguish between metal-associated troilite (Fig. 1) and metal-free troilite (Fig. 2). The first consists of troilite associated or in contact with metal and magnetite (Fig. 1). The association of the three phases is common in Semarkona and other primitive ordinary chondrites, where assemblages of up to several hundreds of microns in size can be found. During thermal metamorphism the connection between the phases in such assemblages makes it likely that Ni diffusion can occur from troilite to metal, thus disturbing the ^{60}Fe - ^{60}Ni system. In contrast, the metal-free troilite is thought to be primary, and no diffusive interaction with metal could have occurred. This troilite is present as aggregates of grains that can have high Fe/Ni ratios, making them ideal objects for the search for possible excesses in ^{60}Ni . Figure 2 shows images and elemental maps of such a metal-free troilite aggregate.

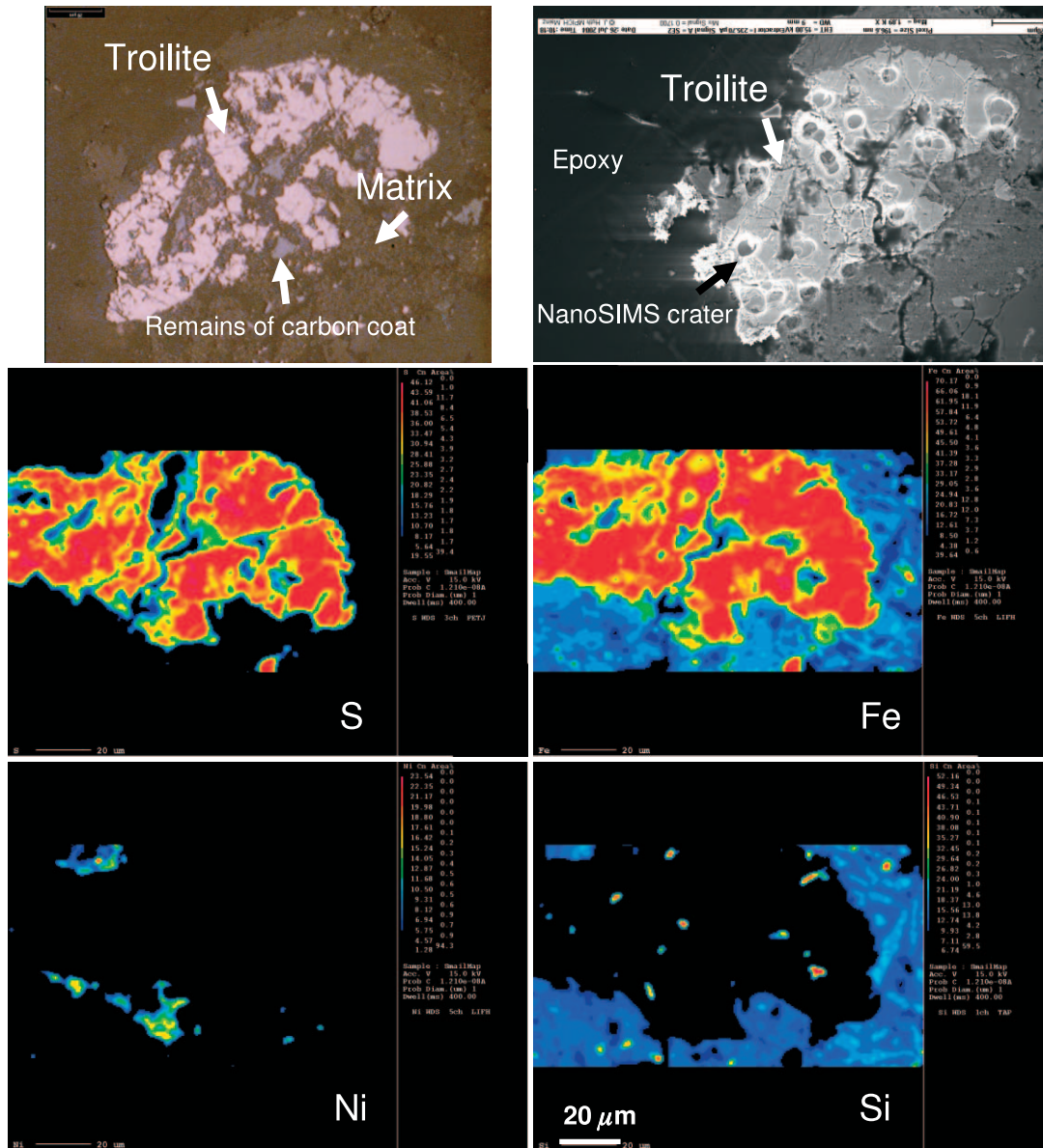


FIG. 2.—Optical microscope and SEM images (*top row*) and elemental maps (S, Fe, Ni, and Si) acquired by EMPA (*middle and bottom rows*; note the rotation compared to the SEM image) of a metal-free troilite aggregate in the Semarkona chondrite. The scale bar is 20 μm in all images.

Although Ni-rich zones are occasionally found in the matrix in close proximity to the troilite, none of those are directly connected with the troilite. We verified that the troilites have sharp edges and display no gradient in Ni concentration that could be explained by interaction with the Ni-rich zones. Since these zones are disconnected from the troilite, we consider them genetically unrelated. In contrast, when testing troilite in contact with metal, the Ni signal increased within the first few cycles of the NanoSIMS measurements, clearly indicating diffusive interaction with the surrounding metal and disturbance of the Fe-Ni system. Our Fe and Ni isotopic measurements were made on six metal-free troilite aggregates and three magnetite assemblages using the NanoSIMS-50 ion microprobe.

3.2. Isotopic Results

Twenty five troilite grains from the six selected metal-free aggregates were measured (Table 1). The $^{56}\text{Fe}/^{58}\text{Ni}$ ratios in the grains range up to $\sim 5 \times 10^4$ (Table 1, Fig. 3). ^{60}Ni excesses were found in all six measured troilite aggregates, with a maximum

$\delta^{60}\text{Ni}$ of $112\% \pm 70\%$ (2σ error). Each data point comprises the results of one to nine measurements on a single troilite grain. While all the data are represented in the diagrams (with 1σ errors), the best-fit lines are calculated only for measurements that we considered statistically acceptable (we limited our calculations to data with $\chi^2 < 1.5$, where χ^2 is the ratio of the standard deviation for $^{60}\text{Ni}/^{62}\text{Ni}$ ratios calculated for each measurement cycle divided by the square root of the number of cycles to the counting statistical error). The diagrams in Figure 3 show a common trend for the troilite aggregates: a clear correlation is seen between ^{60}Ni excesses and $^{56}\text{Fe}/^{58}\text{Ni}$ ratios with $\delta^{60}\text{Ni} = 0$ taken as the origin in some cases. This correlation is taken as definitive evidence for the former existence of live ^{60}Fe in the Semarkona troilites. The best-fit line through all data meeting our statistical criterion (Fig. 4) yields an inferred $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $(0.92 \pm 0.24) \times 10^{-6}$ (2σ error). We verified the consistency of our results through the measurement of three synthetic sulfide minerals (FeS , FeS_2 , and Fe_7S_8), having a large range of Ni concentrations, under the same analytical conditions as for the Semarkona

TABLE 1
Fe-Ni ISOTOPIC RESULTS OF TROILITE AND MAGNETITE IN SEMARKONA

Sample	$\delta^{60}\text{Ni}^a$ (‰)	$^{56}\text{Fe}/^{58}\text{Ni}$
Troilite		
Agg-c1.....	...	...
1.....	1 ± 4	43 ± 3
2.....	10 ± 4	4320 ± 320
3.....	11 ± 4	1190 ± 90
4.....	13 ± 6	7800 ± 580
5.....	17 ± 5	1710 ± 130
6.....	17 ± 5	6040 ± 450
7.....	21 ± 5	3070 ± 230
8.....	23 ± 5	6940 ± 520
9.....	37 ± 6	3960 ± 300
10.....	46 ± 9	14520 ± 1150
Agg-d1.....	...	...
1.....	5 ± 5	120 ± 9
2.....	21 ± 5	4830 ± 2040
3.....	27 ± 8	11960 ± 1350
4.....	31 ± 6	6970 ± 540
5.....	93 ± 49	37000 ± 4320
6.....	112 ± 35	49610 ± 5120
Agg-d2.....	...	...
1.....	14 ± 6	3160 ± 1500
Agg-c1.....	...	...
1.....	12 ± 4	1050 ± 80
2.....	20 ± 7	7300 ± 560
3.....	40 ± 11	16980 ± 1380
4.....	42 ± 8	9990 ± 770
Agg-g12.....	...	...
1.....	25 ± 9	12260 ± 970
2.....	25 ± 15	8810 ± 750
3.....	36 ± 13	6910 ± 570
Agg-h2.....	...	...
1.....	39 ± 7	11080 ± 1360
Magnetite		
Agg-1.....	...	...
1.....	5 ± 4	4720 ± 350
2.....	8 ± 14	35450 ± 2990
3.....	40 ± 21	70570 ± 6420
4.....	65 ± 59	221150 ± 28450
5.....	133 ± 60	514450 ± 64490
Agg-2.....	...	...
6.....	26 ± 49	162950 ± 19540
Agg-3.....	...	...
7.....	55 ± 24	45740 ± 4310

NOTE.—Errors are 1 σ .

^a Here $\delta^{60}\text{Ni} = [(^{60}\text{Ni}/^{62}\text{Ni})_{\text{sample}} / (^{60}\text{Ni}/^{62}\text{Ni})_{\text{standard}} - 1] \times 1000$.

troilite. Figure 5 summarizes our synthetic sulfide results and shows that $\delta^{60}\text{Ni}$ values for all synthetic sulfides are conformably consistent with zero, while the Semarkona data are clearly resolved. This demonstrates that the Semarkona results are real and that there were no analytical problems that could be attributable to instrumental mistuning or to unexpected compositional effects.

The $^{56}\text{Fe}/^{58}\text{Ni}$ ratios in Semarkona magnetite range up to $\sim 5 \times 10^5$ (Table 1). The data, however, show much less radiogenic ^{60}Ni than the troilites (Fig. 6). Because of the very low Ni abundance in high-Fe/Ni regions, the uncertainties in the ^{60}Ni excesses are rather large. Thus, the correlation of the data points is of limited precision. Nevertheless, if a best-fit line is calculated

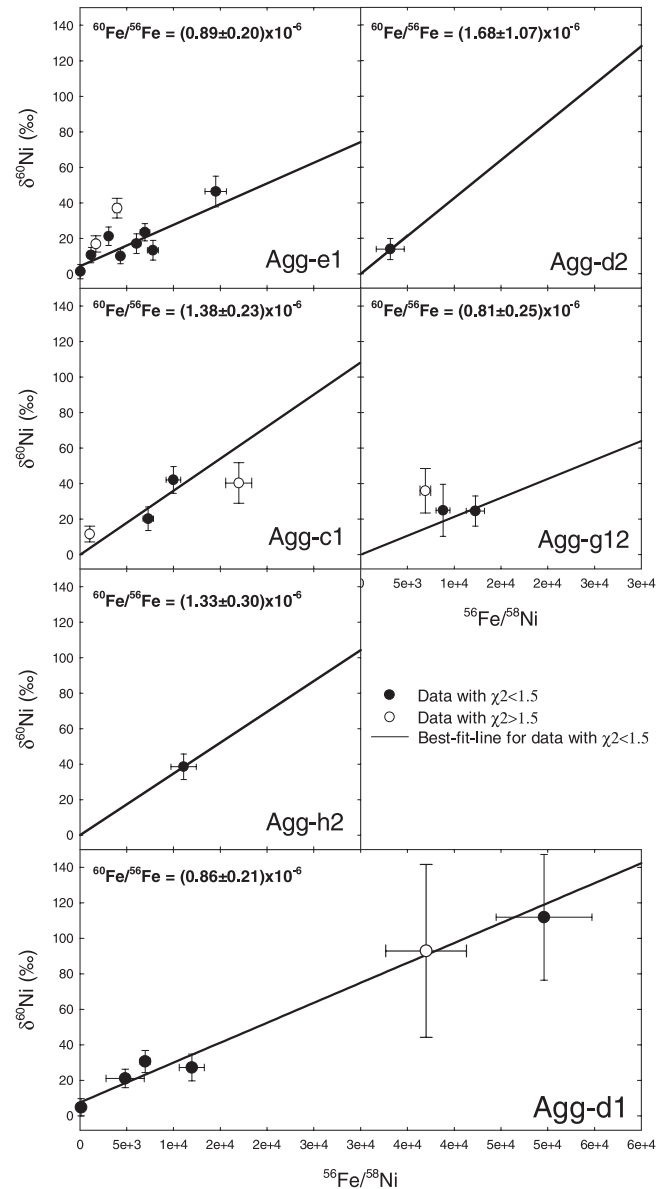


FIG. 3.—Parameter $\delta^{60}\text{Ni}$ as a function of $^{56}\text{Fe}/^{58}\text{Ni}$ for six metal-free troilite aggregates in the Semarkona chondrite. The best-fit lines are calculated for results with $\chi^2 < 1.5$ (filled symbols). Here $\delta^{60}\text{Ni} = [(^{60}\text{Ni}/^{62}\text{Ni})_{\text{sample}} / (^{60}\text{Ni}/^{62}\text{Ni})_{\text{standard}} - 1] \times 1000$. The $^{60}\text{Fe}/^{56}\text{Fe}$ ratios derived from the slopes of each individual aggregate are indicated. For samples c1, d2, g12, and h2 the regression lines were forced through $\delta^{60}\text{Ni} = 0$. All errors are 1 σ .

through the data points, a slope of $(0.11 \pm 0.07) \times 10^{-6}$ (2 σ error) can be deduced. This value is an order of magnitude and significantly lower than that of the troilites.

4. DISCUSSION

4.1. ^{60}Fe - ^{60}Ni System as a Chronometer

The correlation in Figure 4 for Semarkona troilites confirms previous results showing that ^{60}Fe was alive at the birth of the solar system (Shukolyukov & Lugmair 1993). However, the resulting $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $\sim 0.92 \times 10^{-6}$ is the highest measured in any meteorite sample so far and is much higher than previously estimated for the differentiated meteorite Chervony Kut (Shukolyukov & Lugmair 1993). It is also significantly above the ratios reported for troilite in the Bishunpur (L3.1) ordinary chondrite (Tachibana & Huss 2003). Although Bishunpur is

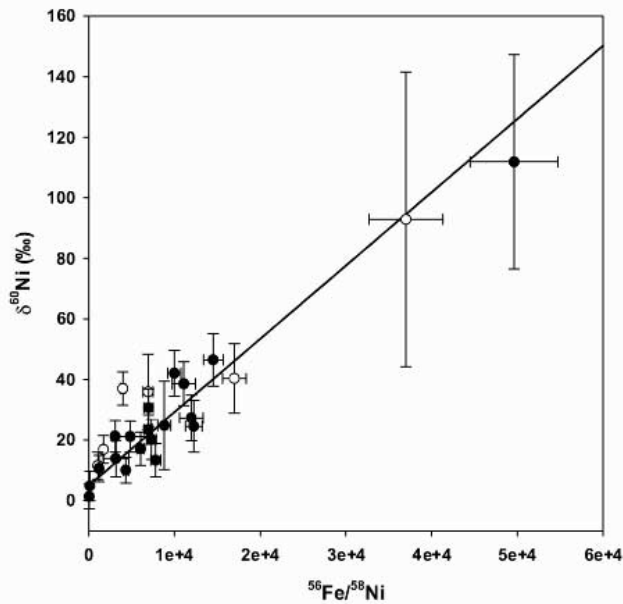


FIG. 4.—Parameter $\delta^{60}\text{Ni}$ as a function of $^{56}\text{Fe}/^{58}\text{Ni}$ for all six metal-free troilite aggregates in the Semarkona chondrite. The slope of the regression line through all data points with $\chi^2 < 1.5$ (filled symbols) corresponds to a $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $(0.92 \pm 0.24) \times 10^{-6}$ (2σ) at the time of formation of these troilites. Errors in the plot are 1σ .

only slightly less primitive than Semarkona, its isotopic results are not surprising because they are all from troilites in contact with metal, where Ni diffusion probably played a significant role in disturbing the ^{60}Fe - ^{60}Ni system and thereby lowering the original slope of the isochron to the measured value. We note that our $^{60}\text{Fe}/^{56}\text{Fe}$ results on magnetite in the metal-troilite-magnetite assemblages are comparable to the results obtained for Bishunpur by Tachibana & Huss (2003).

Our $^{60}\text{Fe}/^{56}\text{Fe}$ ratio in troilite is also higher than that reported for Semarkona chondrule silicates of 2.4×10^{-7} (Huss & Tachibana 2004). This discrepancy could be puzzling, because if the troilite and chondrule silicates in Semarkona originated from the same

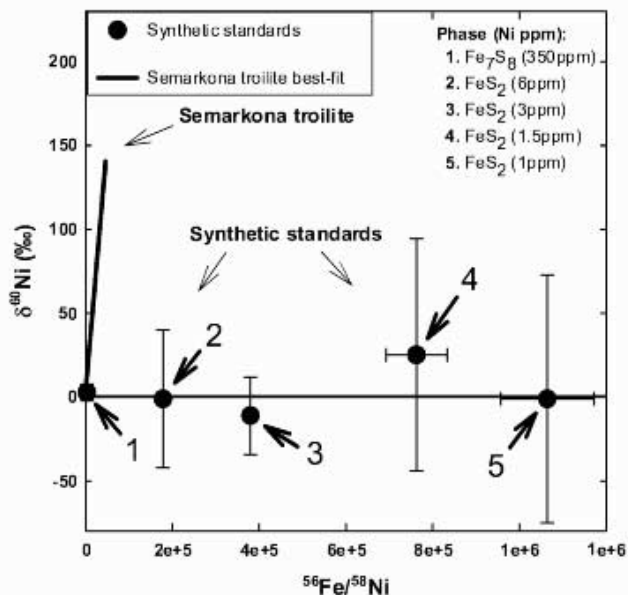


FIG. 5.—Parameter $\delta^{60}\text{Ni}$ as a function of $^{56}\text{Fe}/^{58}\text{Ni}$ for sulfide standards. All data are consistent with $\delta^{60}\text{Ni} = 0$. Errors are 2σ .

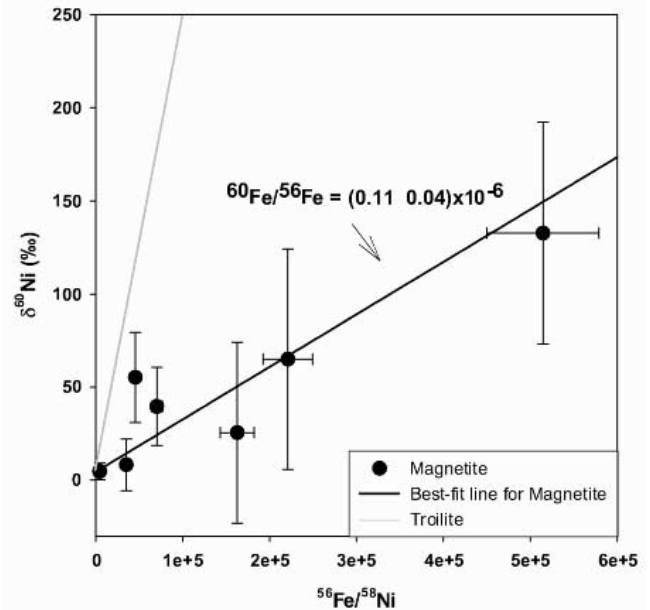


FIG. 6.—Parameter $\delta^{60}\text{Ni}$ as a function of $^{56}\text{Fe}/^{58}\text{Ni}$ for three magnetite assemblages in the Semarkona chondrite. The correlation of the metal-free troilite data from Fig. 4 is also shown for comparison. If the correlation line for the magnetite data is considered an isochron, then the magnetites are ~ 5 Myr younger than the troilites. Errors in the plot are 1σ .

isotopic reservoir, they should reflect similar initial ^{60}Fe abundance in their formation regions. This would point either to a disturbed ^{60}Fe - ^{60}Ni system in one of the studied minerals (e.g., during mild metamorphism) or to a possible analytical bias.

Semarkona is well known as the least equilibrated chondrite preserving original textures and compositions of the matrix. However, its material shows significant aqueous alteration features thought to have been acquired during mild parent body metamorphism (Alexander et al. 1989). In such an event, elemental diffusion could have occurred into or out of the troilite, causing the disturbance of the ^{60}Fe - ^{60}Ni system. However, there are several lines of evidence that the ^{60}Fe - ^{60}Ni system in troilite is not disturbed. First, our data show a clear correlation between $\delta^{60}\text{Ni}$ and $^{56}\text{Fe}/^{58}\text{Ni}$ for the six troilite aggregates. The correlation coefficient in Figure 4 is $r = 0.98$, indicating how well the data points of troilites from different locations within the meteorite fit the same straight line. This contrasts with expectations for a disturbed system, where a previously existing correlation should be randomized. Alteration will definitely not lead to a common trend for all the grains. Second, the troilites we analyzed are fresh grains exhibiting sharp contact with the matrix silicates (Fig. 2). They are all metal-free and they do not contain any alteration products, such as tochilinite, that can help to exchange Ni. Finally, because Fe is a constitutive element of troilite, change of the slope from its original isochron is only expected through Ni mobilization. Experimental studies of troilite by Lauretta (1997) showed that Ni always diffuses out of the troilite. This leads to an increase of the Fe/Ni ratio producing a lower slope. In such a case, the value of the slope should be considered a lower limit of the original isochron. On the other hand, if we assume that isotopically normal Ni has later diffused into the troilite, the original compositions will be changed toward lower $^{56}\text{Fe}/^{58}\text{Ni}$ ratios and $\delta^{60}\text{Ni}$ values. Because both $^{56}\text{Fe}/^{58}\text{Ni}$ and $\delta^{60}\text{Ni}$ are changed by the same factor, the slope remains unaffected. Thus, in whatever direction Ni may have diffused, the slope is considered to be a lower limit for the original isochron.

The discussion above cannot be applied for chondrule silicates, because both Fe and Ni in silicates are mobile. Diffusion of Fe into and/or Ni out of the silicates during metamorphism can lower the slope of an original isochron. However, during mild metamorphism the diffusion rate of cations in pyroxene is known to be limited, even at somewhat higher temperatures (Fujino et al. 1990). Thus, the disturbance of the Fe-Ni system in chondrule silicates due to diffusion is not expected to be pronounced. The significantly lower $^{60}\text{Fe}/^{56}\text{Fe}$ ratio in Semarkona silicates (Huss & Tachibana 2004) could be due to an analytical bias. Silicates contain significant amounts of Ti, and we verified (see above) that it can significantly contribute to the ^{62}Ni signal because of the contribution of the ^{46}TiO tail. We have seen in a chondrule silicate that the ^{46}TiO peak is high in the ^{62}Ni mass region. This will erroneously reduce the measured $^{60}\text{Ni}/^{62}\text{Ni}$ ratio and lead to a lower slope of the original isochron. We thus argue that in order for a silicate result to be reliable, it is compulsory to estimate the contribution of the ^{46}TiO tail, e.g., by measuring Ti-free grains.

As outlined above, we are confident that the $\delta^{60}\text{Ni}$ and $^{56}\text{Fe}/^{58}\text{Ni}$ effects in our Semarkona metal-free troilite are real and that the derived $^{60}\text{Fe}/^{56}\text{Fe}$ ratio is valid. Our $^{60}\text{Fe}/^{56}\text{Fe}$ value approaches the value of 1.6×10^{-6} estimated for a calcium-aluminum-rich inclusion (CAI)³ from the Allende meteorite (Birck & Lugmair 1988). In terms of a chronological interpretation, assuming a common isotopic reservoir for the troilite and CAIs, our value corresponds to a time difference of only about one half-life or less of ^{60}Fe . This would suggest that the Semarkona troilite was formed less than ~ 1 Myr after CAIs, which may indicate that the troilite formed contemporaneously with chondrules. The time of formation of chondrules, 1–2 Myr after CAI formation, was derived from ^{26}Al isotopic data (Kita et al. 2000; Mostefaoui et al. 2002). If the best-fit line for the magnetite data is considered to be an isochron, then the magnetite would have formed at least ~ 5 Myr after the troilite.

The validity of the time interval between formation of CAIs and the Semarkona troilite rests on the assumptions that the estimate for the CAI is reasonable and that these objects have a common isotopic reservoir with an initial $^{60}\text{Fe}/^{56}\text{Fe}$ of 1.6×10^{-6} . The latter assumption leads to the more general question about the uniformity of the isotopic distribution of nuclides in the early solar system. While this is still far from proven, it may be reasonable if the Sun formed within a star cluster or if the collapse of the solar system was even triggered by the explosion of a nearby supernova, which injected freshly produced nuclides into the solar system.

It should be noted, however, that the initial $^{60}\text{Fe}/^{56}\text{Fe}$ value of 1.6×10^{-6} is only an estimate from one CAI from Allende that requires confirmation by additional measurements. Nevertheless, even if the age difference between CAIs and the Semarkona troilite is not valid, the best-fit line in Figure 4 still represents an isochron. Thus, the $^{60}\text{Fe}/^{56}\text{Fe}$ value of 0.92×10^{-6} in the Semarkona troilite should still be considered a lower limit for the solar system initial (SSI) $^{60}\text{Fe}/^{56}\text{Fe}$ ratio.

4.2. Supernova Origin of ^{60}Fe

The high ^{60}Fe abundance obtained for Semarkona troilites can be used to assess and constrain the source of ^{60}Fe . Recent improved models show that short-lived radionuclides are either produced by irradiation with energetic particles from the early Sun (Lee et al. 1998) or synthesized in stars (Wasserburg et al.

1994, 1998; Birck & Lugmair 1988). Model calculations of spallation reactions show that ^{60}Fe cannot be produced efficiently by irradiation (Lee et al. 1998), and the maximum attainable ^{60}Fe abundance is 5 orders of magnitude lower than our present value (Leya et al. 2003). Thus, the ^{60}Fe present at the birth of the solar system must be of a stellar origin. Because of unavoidable co-production of other nuclei, this then will exclude particle irradiation as the sole mechanism responsible for the production of other short-lived radionuclides. In addition, the $^{60}\text{Fe}/^{56}\text{Fe}$ ratio found in this study is much higher than the ^{60}Fe abundance estimated for continuous Galactic evolution (Wasserburg et al. 1996). It also falls well above the values predicted for AGB stars (Wasserburg et al. 1994). However, our $^{60}\text{Fe}/^{56}\text{Fe}$ value falls within the range 3×10^{-7} to 1×10^{-5} predicted for a Type II supernova source (Wasserburg et al. 1998). A likely scenario would then be that ^{60}Fe was freshly synthesized in a nearby supernova explosion and injected into the solar system region. Considering the short half-life of ^{60}Fe , the supernova explosion must have occurred shortly before or during the birth of the solar system, so that live ^{60}Fe could be incorporated into solid objects. This would support a supernova trigger as being responsible for the formation of the solar system (Cameron et al. 1995). However, according to astronomical observations of star-forming regions, supernovae in the vicinity of protostellar clouds are probably not as rare as once thought (Dragicevich et al. 1999 and references therein). Therefore, the supernova that injected ^{60}Fe into the solar system may not have actually triggered its collapse.

4.3. ^{60}Fe as a Heat Source Inducing Planetary Differentiation

The high ^{60}Fe abundance in the early solar system suggests that ^{60}Fe produced sufficient heat to induce planetary melting and differentiation. There is now a growing body of data suggesting that planetary accretion occurred during the very early stages of solar system history (Lugmair & Shukolyukov 1998; Weidenschilling 2000; Kleine et al. 2002; Yin et al. 2002; Foley et al. 2003). According to recent Mn-Cr and particularly Hf-W studies, some metallic cores of asteroids may have formed within the first 3 Myr of solar system existence (Lugmair & Shukolyukov 1998; Kleine et al. 2002; Yin et al. 2002). At that time, ^{60}Fe was still alive and hence would have significantly contributed to planetary melting and differentiation.

For asteroids with radius of more than 30 km, Yoshino et al. (2003) constructed a model describing the production of heat based on the concurrent decay of ^{26}Al and ^{60}Fe in asteroids of chemical compositions similar to carbonaceous chondrites. On the basis of their Figure 2, for a fixed $^{26}\text{Al}/^{27}\text{Al}$ ratio of 7.7×10^{-6} (i.e., ~ 2 Myr after the formation of CAIs), an $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $\sim 10^{-6}$ (a lower limit of the SSI) would be adequate to increase the temperature to levels that lead to melting of asteroidal material within a few million years of accretion. This strongly suggests that ^{60}Fe was an important heat source contributing to planetary melting and differentiation.

Because the half-life of ^{60}Fe is about twice that of ^{26}Al , ^{60}Fe remains extant for a much longer time. This and the geochemical difference between Al and Fe can have severe consequences for the thermal history of asteroids. For instance, for material of chondritic composition and with ^{26}Al abundances of CAIs (i.e., $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$), about 80% of the energy released at the beginning of the decay would come from ^{26}Al . As time passes, the total energy decreases, while the fraction of the energy due to the decay of ^{60}Fe increases. After about 2.5 Myr, ^{60}Fe starts to prevail over ^{26}Al and becomes the dominant source of energy for the remaining time of its decay. After about 3 Myr, when the metallic core is being formed (Kleine et al. 2002; Yin et al.

³ CAIs are millimeter-sized refractory objects thought to be the first objects formed in the solar nebula. These are traditionally used as a reference for relative age determinations of solar system objects.

2002), most of the ^{26}Al has already decayed, while ^{60}Fe , concentrating in the core, is still active. This would result in a massive amount of energy still to be released within the core, well isolated from significant heat loss into space. Thus, asteroids could stay hot and active for a long period of time. This is consistent with recent *Hubble Space Telescope* observations of basaltic regions at the surface of the asteroid Vesta that provide evidence for ancient volcanic activities and lava flows from the interior of the asteroid (Thomas et al. 1997; Lebofsky et al. 1998). An asteroid of the size of Vesta ($R \sim 250$ km) would have remained thermally active during at least the first 15 Myr of its existence, much longer than would be possible from the decay of ^{26}Al alone.

5. SUMMARY

In situ ^{60}Ni anomalies attributable to the decay of short-lived ^{60}Fe were found in troilite and magnetite in the most primitive ordinary chondrite Semarkona (LL 3.0) using the NanoSIMS ion microprobe technique. The troilite shows ^{60}Ni excesses of up to $\sim 100\%$ relative to its solar isotopic abundance. The ^{60}Ni excesses are positively correlated with $^{56}\text{Fe}/^{58}\text{Ni}$ ratios, providing evidence for live ^{60}Fe in the early solar system. The inferred $^{60}\text{Fe}/^{56}\text{Fe}$ ratio of $(0.92 \pm 0.24) \times 10^{-6}$ in troilite is the highest

measured in any meteorite sample so far. This value should be considered a lower limit for the initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratio in the solar system. The magnetite shows much less radiogenic ^{60}Ni than the troilites, suggesting its formation ~ 5 Myr after the troilites.

The inferred $^{60}\text{Fe}/^{56}\text{Fe}$ ratio in the Semarkona troilite falls within the range expected for a Type II supernova source, but outside the predictions for AGB stars. This suggests injection of freshly synthesized ^{60}Fe into the nascent solar nebula by a nearby supernova explosion. This will exclude irradiation with solar energetic particles as the sole mechanism responsible for the production of short-lived radionuclides. The high ^{60}Fe abundance obtained for Semarkona troilites also indicates that the decay of ^{60}Fe must have produced sufficient heat to induce planetary melting and differentiation already in relatively small bodies (>30 km). In large asteroids such as Vesta, ^{60}Fe would have kept the body hot and active for a long period of time.

We are grateful to G. J. MacPherson for the loan of the Semarkona sample. We thank E. Gröner for technical assistance on the NanoSIMS and A. Gorenko for EPMA. Particular thanks go to A. El Goresy for his consistent advice and encouragement and the loan of his synthetic troilite standards.

REFERENCES

- Alexander, C. M. O'd., Barber, D. J., & Hutchison, R. 1989, *Geochim. Cosmochim. Acta*, 53, 3045
- Birck, J. L., & Allegre, J. C. 1985, *Geophys. Res. Lett.*, 12, 745
- Birck, J. L., & Lugmair, G. W. 1988, *Earth Planet. Sci. Lett.*, 90, 131
- Cameron, A. G. W., Höflich, P., Myers, P. C., & Clayton, D. D. 1995, *ApJ*, 447, L53
- Dragicevich, P. M., Blair, D. G., & Burman, R. R. 1999, *MNRAS*, 302, 693
- Foley, C. N., Wadhwa, M., & Janney, P. E. 2003, *Lunar Planet. Sci. Conf.*, 34, 2117
- Fujino, K., Naohara, H., & Momoi, H. 1990, *Eos*, 71, 943
- Huss, G. R., & Tachibana, S. 2004, *Lunar Planet. Sci. Conf.*, 35, 1811
- Hutcheon, I. D., & Hutchison, R. 1989, *Nature*, 337, 238
- Kelley, W. R., & Wasserburg, G. J. 1978, *Geophys. Res. Lett.*, 5, 1079
- Kita, N. T., Nagahara, H., Togashi, S., & Morishita, Y. 2000, *Geochim. Cosmochim. Acta*, 64, 3913
- Kleine, T., Münker, C., Mezger, K., & Palme, H. 2002, *Nature*, 418, 952
- Kutschera, W., et al. 1984, *Nucl. Instrum. Methods Phys. Res. B*, 5, 430
- Lauretta, D. S. 1997, Ph.D. thesis, Washington Univ.
- Lebofsky, L. A., et al. 1998, *BAAS*, 30, 1025
- Lee, T., Papanastassiou, D. A., & Wasserburg, G. J. 1976, *Geophys. Res. Lett.*, 3, 41
- Lee, T., Shu, F. G., Shang, H., Glassgold, A. E., & Rehm, E. 1998, *ApJ*, 506, 898
- Leya, I., Halliday, A. N., & Wieler, R. 2003, *ApJ*, 594, 605
- Lugmair, G. W., Shimamura, T., Lewis, R. S., & Anders, E. 1983, *Science*, 222, 1015
- Lugmair, G. W., & Shukolyukov, A. 1998, *Geochim. Cosmochim. Acta*, 62, 2863
- Mostefaoui, S., Kita, N. T., Togashi, S., Tachibana, S., Nagahara, H., & Morishita, Y. 2002, *Meteoritics Planet. Sci.*, 37, 421
- Reynolds, J. H. 1960, *Phys. Rev. Lett.*, 4, 8
- Shukolyukov, A., & Lugmair, G. W. 1993, *Science*, 259, 1138
- Swindle, T. D., Caffee, M. W., & Hohenberg, C. M. 1988, *Geochim. Cosmochim. Acta*, 52, 2215
- Tachibana, S., & Huss, G. R. 2003, *ApJ*, 588, L41
- Thomas, P. C., Binzel, R. P., Gaffey, M. J., Zellner, B. H., Storrs, A. D., & Wells, E. 1997, *Icarus*, 128, 88
- Urey, H. C. 1955, *Proc. Natl. Acad. Sci.*, 41, 127
- 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
- Weidenschilling, S. J. 2000, *Space Sci. Rev.*, 92, 295
- Yin, Q., Jacobsen, S. B., Yamashita, K., Blichert-Toft, J., Télouk, P., & Albarède, F. 2002, *Nature*, 418, 949
- Yoshino, T., Walter, M., & Katsura, T. 2003, *Nature*, 422, 154