From Dust to Planetesimals: Implications for the Solar Protoplanetary Disk from Short-lived Radionuclides

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Since the publication of the *Protostars and Planets IV* volume in 2000, there have been significant advances in our understanding of the potential sources and distributions of short-lived, now extinct, radionuclides in the early solar system. Based on recent data, there is definitive evidence for the presence of two new short-lived radionuclides (^{10}Be and ^{36}Cl) and a compelling case can be made for revising the estimates of the initial solar system abundances of several others (e.g., ^{26}Al, ^{60}Fe, and ^{182}Hf). The presence of ^{10}Be, which is produced only by spallation reactions, is either the result of irradiation within the solar nebula (a process that possibly also resulted in the production of some of the other short-lived radionuclides) or of trapping of galactic cosmic rays in the protosolar molecular cloud. On the other hand, the latest estimates for the initial solar system abundance of ^{60}Fe, which is produced only by stellar nucleosynthesis, indicate that this short-lived radionuclide (and possibly significant proportions of others with mean lives $\leq$10 m.y.) was injected into the solar nebula from a nearby stellar source. As such, at least two distinct sources (e.g., irradiation and stellar nucleosynthesis) are required to account for the abundances of the short-lived radionuclides estimated to be present in the early solar system. In addition to providing constraints on the sources of material in the solar system, short-lived radionuclides also have the potential to provide fine-scale chronological information for events that occurred in the solar protoplanetary disk. An increasing number of studies are demonstrating the feasibility of applying at least some of these radionuclides as high-resolution chronometers. From these studies, it can be inferred that the millimeter- to centimeter-sized refractory calcium-aluminum-rich inclusions in chondritic meteorites are among the earliest solids to form (at 4567.2 ± 0.6 Ma). Formation of chondrules (i.e., submillimeter-sized ferromagnesian silicate spherules in chondrites) is likely to have occurred over a time span of at least ~3 m.y., with the earliest ones possibly forming contemporaneously with CAIs. Recent work also suggests that the earliest planetesimals began accreting and differentiating within a million years of CAI formation, i.e., essentially contemporaneous with chondrule formation. If so, it is likely that undifferentiated chondrite parent bodies accreted a few million years thereafter, when the short-lived radionuclides that served as the main heat sources for melting planetesimals (^{26}Al and ^{60}Fe) were nearly extinct.

1. INTRODUCTION

Short-lived radionuclides are characterized by half-lives ($T_{1/2}$) that are significantly shorter (i.e., ≤100 m.y.) than the 4.56-Ga age of the solar system. Although now extinct, their former presence at the time of solar system formation can be inferred if variations in their daughter isotopes are demonstrated to correlate with parent/daughter element ratios in meteorites and their components. These radionuclides are of particular interest since (1) an understanding of their sources and distributions in the early solar system (ESS) can provide constraints on the formation environment and astrophysical setting of the solar protoplanetary disk and (2) they have the potential for application as fine-scale chronometers (in many cases with a time resolution of ≤1 m.y.) for events occurring in the early history of the solar system.

A prerequisite for the application of a fine-scale chronometer based on a short-lived radionuclide is that the initial abundance of this radionuclide must be demonstrated to be uniform in the region of the solar system where rocky bodies were forming. Moreover, since the slope of an isochron derived from such a chronometer provides not an age but a measure of the abundance of the radionuclide at the time of last isotopic closure, comparison of the isochron slopes for two separate events can provide only a relative time difference between these events. For such high-resolution relative ages to be mapped on to an absolute timescale, they need to be pinned to a precise time "anchor," which is usually provided by the U-Pb chronometer (which is capable of providing absolute ages with a precision comparable to that of the short-lived chronometers). Further details on the application of short-lived radionuclides as chronometers and the caveats involved have been discussed in several review articles (e.g., *Wasserburg,* 1985; *Podosek and Nichols,* 1997; *Wadhwa and Russell,* 2000; *McKeegan and Davis,* 2003; *Kita et al.,* 2005; *Gounelle and Russell,* 2005).

The purpose of this review is not to provide a comprehensive overview of short-lived radionuclides and their application to the study of meteorites and their components (which may be found in several of the reviews mentioned above). Instead, we will focus on the most recent results and the advances in our understanding of the sources and distributions of these radionuclides since the publication of *Protostars and Planets IV* (PPIV). In the following sections, we will discuss their two main potential sources, i.e., stellar nucleosynthesis and local production by irradiation. Furthermore, based on our current understanding of the abundances and distributions of short-lived radionuclides in the ESS, we will discuss the implications for the astrophysical setting and for the timing of events from "dust to planetesimals" in the solar protoplanetary disk.

2. SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM: THE LATEST RESULTS

Table 1 provides a listing of the short-lived radionuclides for which there is now definitive evidence of their former presence in the ESS, although the initial solar system abundances of some of these are somewhat uncertain. Several others, such as ^{7}Be ($T_{1/2}$ = 53 d) (*Chaussidon et al.,* 2006), ^{99}Tc ($T_{1/2}$ ~ 0.2 m.y.) (*Yin et al.,* 1992), ^{135}Cs ($T_{1/2}$ ~ 2.3 m.y.) (*Hidaka et al.,* 2001) and ^{205}Pb ($T_{1/2}$ ~ 15 m.y.) (*Chen and Wasserburg,* 1987; *Nielsen et al.,* 2004), may also have been present but evidence for these is as yet suggestive rather than definitive.

TABLE 1. Short-lived radionuclides in the early solar system.

Parent Isotope	$T_{1/2}$*	Daughter Isotope	Solar System Initial Abundance†
^{10}Be	1.5	^{10}B	$^{10}Be/^{9}Be \approx 10^{-3}$
^{26}Al	0.72	^{26}Mg	$^{26}Al/^{27}Al \approx 5–7 \times 10^{-5}$
^{36}Cl	0.3	^{36}Ar (98.1%) ^{36}S (1.9%)	$^{36}Cl/^{35}Cl \geq 1.6 \times 10^{-4}$
^{41}Ca	0.1	^{41}K	$^{41}Ca/^{40}Ca \geq 1.5 \times 10^{-8}$
^{53}Mn	3.7	^{53}Cr	$^{53}Mn/^{55}Mn \approx 10^{-5}$
^{60}Fe	1.5	^{60}Ni	$^{60}Fe/^{56}Fe \approx 3–10 \times 10^{-7}$
^{92}Nb	36	^{92}Zr	$^{92}Nb/^{93}Nb \approx 10^{-5}–10^{-3}$
^{107}Pd	6.5	^{107}Ag	$^{107}Pd/^{108}Pd \approx 5–40 \times 10^{-5}$
^{129}I	15.7	^{129}Xe	$^{129}I/^{129}Xe \approx 10^{-4}$
^{146}Sm	103	^{142}Nd	$^{146}Sm/^{144}Sm \approx 7 \times 10^{-3}$
^{182}Hf	8.9	^{182}W	$^{182}Hf/^{180}Hf \approx 10^{-4}$
^{244}Pu	82	Fission Xe	$^{244}Pu/^{238}U \approx 7 \times 10^{-3}$

*Half-life in millions of years.

†Data sources: ^{10}Be: *McKeegan et al.* (2000); ^{26}Al: *Lee et al.* (1976), *MacPherson et al.* (1995), *Bizzarro et al.* (2004), *Young et al.* (2005); ^{36}Cl: *Lin et al.* (2005); ^{41}Ca: *Srinivasan et al.* (1994, 1996); ^{53}Mn: *Lugmair and Shukolyukov* (1998); ^{60}Fe: *Tachibana and Huss* (2003), *Mostefaoui et al.* (2005), *Tachibana et al.* (2006); ^{92}Nb: *Harper* (1996), *Münker et al.* (2000), *Sanloup et al.* (2000), *Yin et al.* (2000), *Schönbächler et al.* (2002); ^{107}Pd: *Chen and Wasserburg* (1996), *Carlson and Hauri* (2001); ^{129}I: *Swindle and Podosek* (1988) and references therein, *Brazzle et al.* (1999); ^{146}Sm: *Lugmair and Galer* (1992) and references therein; ^{182}Hf: *Kleine et al.,* (2002, 2005), *Yin et al.* (2002); ^{244}Pu: *Podosek* (1970), *Hudson et al.* (1989).

Since PPIV, two new short-lived radionuclides (^{10}Be and ^{36}Cl) have been added to the roster of those for which there is now compelling evidence for their former presence in the ESS (Table 1). In addition, the presence of ^{92}Nb, for which there was only suggestive evidence prior to 2000, has been confirmed by several recent studies, although its initial abundance is still debated. Also, on the basis of recent analyses of meteorites and their components, the initial abundances of several of the short-lived radionuclides listed in Table 1 have been revised. Some of the implications of these new results will be discussed in the following sections.

2.1. Beryllium-10

McKeegan et al. (2000) showed that excesses in $^{10}B/^{11}B$ are correlated with $^{9}Be/^{11}B$ ratios in calcium-aluminum-rich inclusions (CAI) from the Allende carbonaceous chondrite, indicating an initial $^{10}Be/^{9}Be$ ratio of ~10^{-3} in the ESS (Fig. 1). Subsequently, additional studies of CAIs from other chondrite groups have confirmed this finding (*Sugiura et al.,* 2001; *Marhas et al.,* 2002; *MacPherson et al.,* 2003).

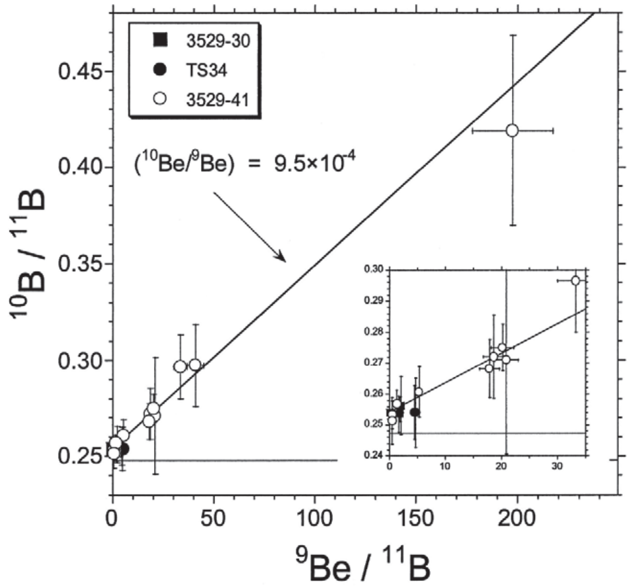

Fig. 1. Boron-isotopic composition of Allende CAIs vs. Be/B ratios (*McKeegan et al.,* 2000).

2.2. Chlorine-36

Recently, *Lin et al.* (2005) presented new evidence (excesses in ^{36}S that correlated with Cl/S ratios) for the presence of live ^{36}Cl in sodalite, a chlorine-rich mineral that most likely formed from aqueous alteration on the parent body, in a CAI from the Ningqiang carbonaceous chondrite (Fig. 2). This work indicates that the ^{36}Cl/^{35}Cl ratio in the ESS was at least ~1.6×10^{-4}.

2.3. Niobium-92

Until just a few years ago, the only hint of the former presence of ^{92}Nb in the ESS had been a well-resolved excess of ^{92}Zr in rutile, a rare mineral with a high Nb/Zr ratio, in the Toluca iron meteorite, based upon which an initial ^{92}Nb/^{93}Nb ratio of ~2×10^{-5} was inferred for the solar system (*Harper,* 1996). Subsequently, several studies also reported excesses in ^{92}Zr in bulk samples and mineral separates from a variety of primitive and differentiated meteorites, but suggested a substantially higher initial ^{92}Nb/^{93}Nb ratio of ~10^{-3} (*Münker et al.,* 2000; *Sanloup et al.,* 2000; *Yin et al.,* 2000). However, *Schönbächler et al.* (2002) reported internal ^{92}Nb-^{92}Zr isochrons for the H6 chondrite Estacado and a basaltic clast from the Vaca Muerta mesosiderite and inferred an initial solar system ^{92}Nb/^{93}Nb ratio of ~10^{-5}. *Yin and Jacobsen* (2002) have suggested that Estacado and the Vaca Muerta clast may record secondary events that postdated solar system formation by ~150 ± 20 m.y. If so, the lower ^{92}Nb/^{93}Nb ratio inferred by *Schönbächler et al.* (2002) would be compatible with the higher value of ~10^{-3} (which would then reflect the true initial value) reported by others (*Münker et al.,* 2000; *Sanloup et al.,* 2000; *Yin et al.,* 2000). Although the ^{40}Ar-^{39}Ar ages for Estacado (*Flohs,* 1981) and the ^{147}Sm-^{143}Nd ages for Vaca Muerta clasts (*Stewart et al.,* 1994) may indeed record late disturbances >100 m.y. after the beginning of the solar system, there is no definitive indicator that the Nb-Zr system was reset in these samples at this time. As such, the initial abundance of ^{92}Nb in the ESS is as yet unclear.

2.4. Initial Abundances of Aluminum-26, Calcium-41, Iron-60, and Hafnium-182

The initial abundances of several of the radionuclides listed in Table 1 have been revised significantly since PPIV. Until recently, the initial ^{26}Al/^{27}Al ratio in the ESS was thought to have the canonical value of ~5×10^{-5} (*Lee et al.,* 1976; *MacPherson et al.,* 1995). However, recent high-precision Mg-isotopic analyses of CAIs indicate that the initial ^{26}Al/^{27}Al ratio may have been as high as 6–7 × 10^{-5} (*Bizzarro et al.,* 2004, 2005a; *Young et al.,* 2005; *Taylor et al.,* 2005). If this higher value for the initial ^{26}Al/^{27}Al ratio is assumed, then the initial ^{41}Ca/^{40}Ca ratio may also have been correspondingly higher than the previously inferred value of ~1.5×10^{-8} by at least an order of magnitude, because the initial ^{41}Ca/^{40}Ca ratio was measured on CAIs with internal isochrons indicating an initial ^{26}Al/^{27}Al ratio of ~5×10^{-5}.

Although *Birck and Lugmair* (1988) had noted excesses in ^{60}Ni in Allende CAIs, these could be attributable to nucleosynthetic anomalies and the first definitive evidence for the presence of live ^{60}Fe in the ESS came from the work of *Shukolyukov and Lugmair* (1993a,b). These authors showed that excesses in ^{60}Ni were correlated with Fe/Ni ratios in bulk samples of the eucrites Chervony Kut and Juvinas. Based on their analyses, *Shukolyukov and Lugmair*

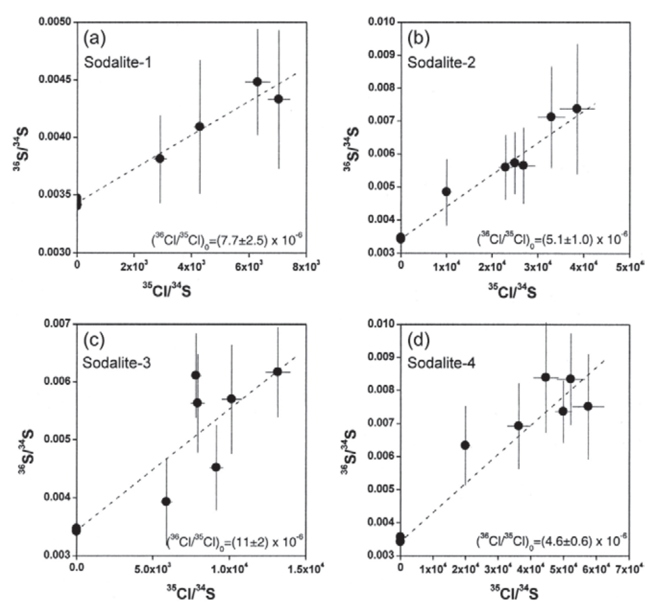

Fig. 2. Sulfur-isotopic compositions of sodalite-rich assemblages in a Ningqiang CAI (*Lin et al.,* 2005). The best inferred ^{36}Cl/^{35}Cl ratio from these data is 5×10^{-6}. Assuming that the sodalites formed ≥1.5 m.y. after CAIs, an initial ^{36}Cl/^{35}Cl ratio of ≥1.6 × 10^{-4} is inferred.

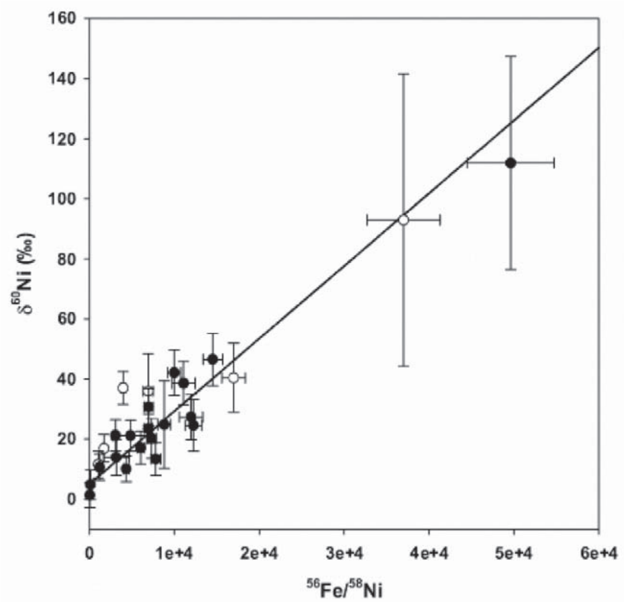

Fig. 3. Excesses in the $^{60}Ni/^{62}Ni$ ratio relative to a terrestrial standard in parts per 10^3 vs. Fe/Ni ratios in troilites from metal-free assemblages in the Semarkona unequilibrated ordinary chondrite (*Mostefaoui et al.,* 2005). The slope of the Fe-Ni isochron yields a $^{60}Fe/^{56}Fe$ ratio of $(0.92 \pm 0.24) \times 10^{-6}$.

(1993a,b) inferred an initial $^{60}Fe/^{56}Fe$ ratio of ~10^{-8}. Recently, ion microprobe analyses of components in unequilibrated chondrite meteorites indicate that the initial solar system $^{60}Fe/^{56}Fe$ ratio is likely to be as high as ~10^{-6} (*Tachibana et al.,* 2006; *Mostefaoui et al.,* 2005) (Fig. 3). The lower initial $^{60}Fe/^{56}Fe$ ratio inferred from the eucrites (which are known to have undergone varying degrees of thermal metamorphism) is thought to be the result of partial equilibration of the Fe-Ni system.

The earliest estimates of an upper limit on the initial $^{182}Hf/^{180}Hf$ ratio for the ESS based on analyses of meteoritic material suggested that it was ≤~2×10^{-4} (*Ireland,* 1991; *Harper and Jacobsen,* 1996). Subsequently, the work of *Lee and Halliday* (1995, 1996) indicated that the W isotope composition of the bulk silicate Earth (BSE) was identical to that of the chondrites and the initial $^{182}Hf/^{180}Hf$ ratio for the ESS was ~2.5×10^{-4}. However, several recent studies demonstrated that the W isotope composition of the BSE is more radiogenic than chondrites by ~2ε units (*Kleine et al.,* 2002; *Schoenberg et al.,* 2002; *Yin et al.,* 2002) and indicated a lower initial $^{182}Hf/^{180}Hf$ ratio of ~1×10^{-4} (note that W isotope composition in ε units or ε^{182}W is defined as the $^{182}W/^{183}W$ or the $^{182}W/^{184}W$ ratio relative to the terrestrial standard in parts per 10^4). Based on the extremely unradiogenic W isotope composition of the Tlacotepec iron meteorite, *Quitté and Birck* (2004) suggested an intermediate value of ~1.6×10^{-4} for the initial $^{182}Hf/^{180}Hf$ ratio. However, the highly unradiogenic ε^{182}W values reported in some iron meteorites, i.e., lower than the initial value of –3.5ε units inferred from chondrites and their components, may be due to burnout of W isotopes from long exposure to galactic cosmic rays (GCRs) (*Markowski et al.,* 2006; *Qin et al.,* 2005). Two recent Hf-W studies of meteoritic zircons (which are good candidates for Hf-W chronometry owing to their typically high Hf/W ratios) provide somewhat conflicting results. *Ireland and Bukovanská* (2003) confirmed an initial $^{182}Hf/^{180}Hf$ ratio based on Hf-W systematics in zircons from the H5 chondrite Simmern of close to ~1×10^{-4}. These authors also reported Hf-W systematics in zircons from the Pomozdino eucrite that gave a substantially lower $^{182}Hf/^{180}Hf$ ratio of ~2×10^{-5}, perhaps suggestive of late-metamorphic resetting in this eucrite. In contrast, *Srinivasan et al.* (2004), who analyzed Hf-W and U-Pb systematics in zircons from another eucrite, have suggested the initial $^{182}Hf/^{180}Hf$ ratio was at least ~3×10^{-4}. The reason for these apparently discrepant values for the initial $^{182}Hf/^{180}Hf$ ratio is not clear. Nevertheless, the most recent work on the W isotopes in CAIs appears to support an initial $^{182}Hf/^{180}Hf$ ratio of ~1×10^{-4} (*Kleine et al.,* 2005).

3. SOURCES OF SHORT-LIVED RADIONUCLIDES AND THEIR IMPLICATIONS

3.1. Stellar Nucleosynthesis

Most of the short-lived radioactive nuclides present in the ESS could be produced and ejected from stars. In this section we briefly review the stellar synthesis of these isotopes and discuss possible implications for their distribution in the solar nebula.

3.1.1. Aluminum-26. Aluminum-26 is produced in hydrogen burning by the reactions $^{25}Mg(p,\gamma)^{26}Al$ and $^{26}Mg(p,n)^{26}Al$. Such ^{26}Al may be ejected from dredged-up hydrogen-shell-burning material in low-mass stars (stars with masses less than about 8 $M_\odot$) during their red giant branch (RGB) or asymptotic giant branch (AGB) phases or from high-mass stars (stars with masses greater than roughly 10 $M_\odot$) when they explode as core-collapse supernovae. This radioisotope is also made during carbon burning as neutrons and protons liberated in the fusion of two carbon nuclei drive capture reactions on Mg isotopes. Carbon-burning-produced ^{26}Al would only be ejected from massive stars.

3.1.2. Chlorine-36 and calcium-41. The isotopes ^{36}Cl and ^{41}Ca are synthesized in *s*-process nucleosynthesis, predominantly during core helium burning in massive stars. Production of ^{36}Cl and ^{41}Ca also occurs during explosive oxygen burning in supernova events.

3.1.3. Manganese-53. Manganese-53 is produced predominantly in silicon burning with some contribution from oxygen burning. While production of ^{53}Mn does occur in the presupernova evolution of a massive star, most of the ^{53}Mn ejected is synthesized during the explosive phase as the shock wave generated by the stellar collapse passes through silicon- and oxygen-rich layers of the star. These layers lie near the boundary between what escapes the star and what remains behind in the neutron star or black hole resulting from the explosion. A roughly comparable amount is made in typical Type Ia supernovae, which are thermonuclear explosions of white dwarf stars. Manganese-53 is not produced in low-mass stars.

3.1.4. Iron-60. Iron-60 cannot be produced in any significant amount during mainline *s*-processing since the short lifetime of ^{59}Fe prevents much neutron capture flow to heavier isotopes of Fe. The later stage of carbon burning achieves a higher neutron density and allows for significant production of ^{60}Fe, a fact that strongly favors massive stars as the site of production of this isotope. Most of the ^{60}Fe ejected from stars, however, is likely produced in explosive carbon burning during the supernova explosion with significant production also occurring in the neutron burst in the helium shell (e.g., *Meyer,* 2005). Significant production may occur in higher-mass AGB stars (e.g., *Gallino et al.,* 2004) and some may even occur in the rare deflagrating or detonating white dwarf stars that likely produced the bulk of the solar system's supply of ^{48}Ca (*Meyer et al.,* 1996; *Woosley,* 1997), but the yield from these events is not yet certain.

3.1.5. Palladium-107, iodine-129, hafnium-182, and plutonium-244. The isotopes ^{107}Pd, ^{129}I, ^{182}Hf, and ^{244}Pu are produced by the *r*-process of nucleosynthesis whose site is not yet determined. The most promising setting for the *r*-process is in neutrino-heated ejecta from core-collapse supernovae (e.g., *Woosley et al.,* 1994); however, tidal disruptions of neutron stars have not been ruled out (e.g., *Freiburghaus et al.,* 1999). Palladium-107 is also produced in the *s*-process of nucleosynthesis, which occurs when neutrons liberated by the reaction $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ are subsequently captured by heavier seed nuclei. This production may occur in AGB stars during shell helium burning or in massive stars during core or shell helium burning (*Gallino et al.,* 2004). Importantly, ^{129}I and ^{182}Hf are also produced in the neutron burst that occurs in the inner parts of the helium-rich shell in the massive star during a supernova explosion (e.g., *Meyer,* 2005). This neutron burst contributes only a small amount of the ^{129}I and ^{182}Hf that has ever existed in the galaxy; however, it may have contributed a dominant portion of the abundance of these isotopes present in the ESS. It is important to note, however, that a neutron burst will not produce ^{244}Pu since the seed uranium or thorium nuclei would have been burned up by *s*-processing prior to the neutron burst. Any ^{244}Pu alive in the ESS must have been a residue of galactic *r*-process nucleosynthesis.

3.1.6. Niobium-92 and samarium-146. A handful of heavy, proton-rich nuclei are bypassed by neutron capture processes. These nuclei are made in a separate process, known as the *p*-process, which is thought to occur in core-collapse supernovae as the shock wave passes through the oxygen-/neon-rich layers of a massive star during the stellar explosion. The heating due to shock passage causes first neutrons, then protons and α particles to disintegrate from preexisting seed nuclei. Once this disintegration process freezes out, a distribution of proton-rich nuclei remains. This synthesis process is also known in the literature as the γ-process (*Woosley and Howard,* 1978; *Arnould and Goriely,* 2003). It is also possible that the γ-process occurs in the outer layers of a Type Ia supernova if the burning front is a deflagration when it reaches the surface (*Howard et al.,* 1991).

While the γ-process can account for the abundance of heavy *p*-process nuclei, including ^{146}Sm, it falls short of producing the light *p*-nuclei, particularly the *p*-process isotopes of molybdenum and ruthenium. It is therefore likely that some other process is responsible for the bulk production of those isotopes, and, concomitantly, for ^{92}Nb. The most promising process is the freeze-out from high-entropy nuclear statistical equilibrium near the mass cut of a core-collapse supernova (e.g., *Fuller and Meyer,* 1995; *Hoffman et al.,* 1996). Interactions between nuclei and the copious supply of supernova neutrinos may be necessary to account for the proper supply of *p*-process isotopes of molybdenum, ruthenium, and niobium (e.g., *Meyer,* 2003; *Frölich et al.,* 2006).

Table 2 summarizes the above discussion. The nucleosynthesis processes delineated above synthesized the short-lived isotopes over the course of the galaxy's evolution. A steady-state abundance of these isotopes developed in the interstellar medium (ISM) as the rate of production in stars

TABLE 2. Stellar nucleosynthetic processes and sources of short-lived radionuclides.

Isotope	Nucleosynthesis Process	Site
^{26}Al	Hydrogen burning	MS, RGB, AGB
	Carbon burning	MS
^{36}Cl	*s*-process	MS, AGB
	Oxygen burning	MS
^{41}Ca	*s*-process	MS, AGB
	Oxygen burning	MS
^{53}Mn	Silicon burning	MS
	NSE	SNIa
^{60}Fe	Carbon burning	MS
	Neutron burst	MS
	s-process	AGB
	Neutron-rich NSE	Rare SNIa
^{92}Nb	*p*-process	MS, SNIa
^{107}Pd	*r*-process	MS, NS
	s-process	MS, AGB
^{129}I	*r*-process	MS, NS
	Neutron burst	MS
^{146}Sm	*p*-process	MS, SNIa
^{182}Hf	*r*-process	MS, NS
	Neutron burst	MS
^{244}Pu	*r*-process	MS, NS

MS = massive star; RGB = red giant branch star; AGB = asymptotic giant branch star; SNIa = Type Ia supernova; NS = neutron star disruptions; NSE = nuclear statistical equilibrium.

came to balance the rate of destruction by decay and astration. The solar system inherited this ISM abundance. Since we expect the dust and gas that carried the short-lived radionuclides into the solar cloud to be fairly well mixed, we would therefore expect a reasonably uniform distribution of these radionuclides in the protosolar cloud and a well-defined value for their abundance when the minerals to be dated were formed. Such results would make these isotopes valid chronometers.

These conclusions, however, rely on the assumption that the abundances in the early solar nebula are those of the steady-state ISM. This is probably true for the longer-lived isotopes such as ^{92}Nb, ^{146}Sm, and ^{244}Pu but possibly also ^{53}Mn (e.g., *Meyer and Clayton,* 2000); however, it is not for ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe. These isotopes had ESS abundances greater than those expected from a steady-state ISM. A plausible explanation for the high abundance of ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe is that the bulk of these isotopes in the early solar nebula were injected by a supernova that may have triggered the collapse of the solar cloud (e.g., *Cameron and Truran,* 1977; *Cameron et al.,* 1995; *Meyer and Clayton,* 2000) or were injected directly into the protoplanetary disk (*Ouellette et al.,* 2005). Remarkably, such a supernova could also have injected significant amounts of ^{129}I and ^{182}Hf as well (e.g., *Meyer,* 2005). The actual manner in which the short-lived radionuclides were injected remains to be worked out. Therefore, it is conceivable that the injection process could have given rise to an inhomogeneous distribution of these radionuclides. Such a result could cloud their use as chronometers; however, the lack of collateral anomalies in stable isotopes argues against such an inhomogeneous injection (*Nichols et al.,* 1999).

3.2. Local Production

Production of the isotopes of elements lighter than Fe via irradiation of matter in the solar accretion disk by high-energy particles (>MeV) has long been considered as a promising alternative path to stellar nucleosynthesis (*Fowler et al.,* 1962). The discovery that ^{26}Al was alive in the solar accretion disk (*Lee et al.,* 1976) prompted studies examining its production via proton irradiation (e.g., *Heymann and Dziczkaniec,* 1976; *Lee,* 1978). These authors estimated that large fluences were needed to reproduce the observed ^{26}Al abundance. In the absence of experimental evidence for elevated fluences, irradiation failed to be considered as a viable means of producing short-lived radionuclides until recently revived by *Lee et al.* (1998).

At present, experimental results support the possibility that some short-lived radionuclides were produced by irradiation. First, it is now well established that virtually all low-mass stars display an enhanced X-ray activity (*Feigelson et al.,* 2002; *Wolk et al.,* 2005). Radio observations of young stellar objects (YSOs) have resulted in the direct detection of gyrosynchrotron radiation from MeV electrons (*Güdel,* 2002). YSOs also show hard X-ray spectra associated with violent magnetic reconnection flares and baryon acceleration at energies up to hundreds of MeV/A (*Wolk et al.,* 2005). A second evidence in favor of irradiation within the ESS could be the ubiquitous presence of ^{10}Be at the time of formation of CAIs (*McKeegan et al.,* 2000; *Marhas et al.,* 2002; *MacPherson et al.,* 2003) and the possible presence of ^{7}Be at the time of formation of the Allende CAI 3529-41 (*Chaussidon et al.,* 2006).

Trapping of GCRs in the protosolar molecular cloud core likely contributed at some level to the initial abundance of ^{10}Be in the ESS and possibly accounted for all of it (*Desch et al.,* 2004), but GCRs are not likely to have contributed significantly to other radionuclides. For example, <0.1% of the solar system's initial abundance of ^{26}Al is attributable to GCRs (*Desch et al.,* 2004). While this alternative origin is a viable one for ^{10}Be, it is also feasible that some or all of it has an irradiation origin within the solar system (*McKeegan et al.,* 2000; *Gounelle et al.,* 2001; *Marhas and Goswami,* 2004). The very short half-life of ^{7}Be ($T_{1/2}$ = 53 d) precludes its origin outside the solar system. Therefore, if its presence can be confirmed by further analyses, it would establish a definitive proof of irradiation within the ESS.

In any irradiation model, the main parameters are the proton flux, the irradiation duration, the abundance of heavier cosmic rays (^{3}He, ^{4}He) relative to protons, the target abundance, the nuclear cross sections, and the energy spectrum of protons (*Chaussidon and Gounelle,* 2006). What mainly distinguishes the different irradiation models are (1) the astrophysical context of irradiation, (2) the physical nature of the targets (solid or gaseous), (3) the chemistry of the targets, and (4) the location of the irradiated targets relative to the source of the cosmic rays. The proton energy spectrum is usually considered to satisfy a power law, $N(E) \sim E^{-p}$, with varying index p. Models considering irradiation in the context of the progenitor molecular cloud (e.g., *Clayton and Jin,* 1995) failed at reproducing the observed abundances of ^{26}Al, ^{41}Ca, and ^{53}Mn, and have now fallen into abeyance. As such, the most likely astrophysical context for irradiation synthesis of short-lived radionuclides is the solar accretion disk. In this context, it is recognized that the Sun's magnetic activity consists of two broad classes of events. Gradual events emitting soft X-rays are electron- and ^{3}He-poor. More frequent impulsive events emit hard X-rays and are electron- and ^{3}He-rich (*Reames,* 1995). Impulsive flares have steeper energy spectra than gradual flares.

Goswami et al. (2001), followed by *Marhas et al.* (2002) and *Marhas and Goswami* (2004), developed models examining the possibility of producing short-lived radionuclides by irradiation of solar system dust by proton and ^{4}He nuclei at asteroidal distances. In these studies, shielding of the whole solar accretion disk is neglected and accelerated solar particles are supposed to have free access to dust at ~3 AU. These authors limited their models to examining gradual events having shallow proton energy spectra ($p < 3$) and normalized their yields to ^{10}Be. Based on these models, *Marhas and Goswami* (2004) contended that irradiation could account for all the ^{10}Be, 10–20% of ^{41}Ca and ^{53}Mn, and none of the ^{26}Al inferred to be present in the ESS.

Lee et al. (1998) first examined the possibility that some short-lived radionuclides could be synthesized by irradiation in the context of the X-wind theory of low-mass star formation (*Shu et al.,* 1996), introducing three important conceptual modifications compared to previous models: (1) Irradiation takes place close to the Sun, in a gas-poor region (i.e., the reconnection ring where magnetic lines tying the protostar and the accretion disks reconnect), providing a powerful mechanism for accelerating ^{1}H, ^{3}He, and ^{4}He nuclei to energies up to a few tens of MeV. The X-wind provides a natural transport mechanism from the regions close to the Sun to asteroidal distances (*Shu et al.,* 1996). (2) The X-wind model has opened the ^{3}He channel for the production of short-lived radionuclides, enhancing the ^{26}Al production via the reaction ^{24}Mg(^{3}He,p)^{26}Al. (3) It calculates absolute yields instead of yields relative to a given short-lived radionuclide (such as ^{10}Be), scaling the proton flux to observations of X-ray protostars. In this model, ^{26}Al and ^{53}Mn are produced at their observed abundance for parameters corresponding to impulsive events (p = 3.5, ^{3}He/^{1}H = 1.4). Calcium-41 is overproduced by 2 orders of magnitude relative to its observed abundance, while ^{60}Fe is underproduced by several orders of magnitude. *Gounelle et al.* (2001) refined this model, and calculated yields of the recently discovered ^{10}Be (*McKeegan et al.,* 2000). The production of ^{10}Be (as well as ^{26}Al and ^{53}Mn) was found to agree with the observed value in the case of impulsive events (p = 4, ^{3}He/^{1}H = 0.3). They also proposed that the ^{41}Ca overproduction could be alleviated if proto-CAIs had a layered structure (*Shu et al.,* 2001). Using the same model and a preliminary estimate of ^{7}Be nuclear cross sections, *Gounelle et al.* (2003) calculated a ^{7}Be/^{9}Be ratio of ~0.003, at odds with the initial claim by *Chaussidon et al.* (2002) of ^{7}Be/^{9}Be up to ~0.22 inferred in an Allende CAI. Subsequently, *Chaussidon et al.* (2006) revised their estimate of the ^{7}Be/^{9}Be ratio to ~0.005, compatible within a factor of 2 with the X-wind model prediction. The ability of the X-wind model to produce a relatively high abundance of ^{7}Be despite its very short half-life is due to the high flux of accelerated particles adopted since *Lee et al.* (1998). This contrasts with the otherwise similar model of *Leya et al.* (2003) that invokes special conditions for the production of ^{7}Be. The yields of ^{36}Cl presented in *Gounelle et al.* (2006) are slightly lower than the observed value (*Lin et al.,* 2005), but still in line with it, given the model uncertainties (^{36}Cl-producing cross sections have not been experimentally determined). Furthermore, if the initial solar system abundance of ^{26}Al was indeed supercanonical (*Young et al.,* 2005), the initial ^{41}Ca/^{40}Ca ratio was probably higher than 1.5×10^{-8}. Therefore, a layered structure of CAIs may no longer be required to account for the ^{41}Ca abundance (*Gounelle et al.,* 2006). The decoupling of ^{10}Be and ^{26}Al observed in some hibonites (*Marhas et al.,* 2002) may be accounted for by irradiation during gradual events instead of impulsive ones (*Gounelle et al.,* 2006).

To summarize, it is recognized that irradiation at asteroidal distances using "normal" proton fluences and gradual events fails to produce the observed amount of short-lived radionuclides such as ^{26}Al, ^{41}Ca, and ^{53}Mn (*Goswami et al.,* 2001). However, there is strong evidence that the proton fluence of protostars was $10^{5}\times$ higher than at present (*Feigelson et al.,* 2002), and that there was intensive radial transport from the inner disk to larger heliocentric distances (*Wooden et al.,* 2004), either via turbulence (*Cuzzi et al.,* 2003) or by X-wind (*Shu et al.,* 1996). The specific irradiation model developed in the context of the X-wind theory can reproduce the observed abundances of ^{7}Be, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn within uncertainties for cosmic-ray parameters corresponding to impulsive events. X-ray observations have shown that the impulsive phase is often present in YSOs (*Wolk et al.,* 2005).

Uncertainties of the model arise mainly from poor knowledge of the nuclear cross sections, especially for the ^{3}He channel. To reduce these uncertainties, nuclear physicists based at Orsay have undertaken the measurement of ^{3}He-induced cross sections (*Fitoussi et al.,* 2004). They found that the experimental ^{24}Mg(^{3}He,p)^{26}Al cross section is a factor of ~2 to 3 lower than the estimate of *Lee et al.* (1998), but within the range of the reported uncertainties.

At present, it is not yet clear how much irradiation processes contributed to the inventory of short-lived radionuclides. X-ray observations of protostars and realistic models reproducing the observed initial abundances of a handful of these radionuclides call for further investigation of this possibility.

4. ASTROPHYSICAL SETTING OF THE SOLAR PROTOPLANETARY DISK

The presence of short-lived radionuclides with half-lives ≪10 m.y. in the ESS, at initial abundances noted in Table 1, provides a record of the dramatic processes occurring within a few million years of the solar system's birth. This contrasts with the case for the relatively longer-lived radionuclides such as ^{146}Sm ($T_{1/2}$ ~ 103 m.y.) and ^{244}Pu ($T_{1/2}$ ~ 82 m.y.). As mentioned in the previous section, supernovae, novae, and AGB stars maintain steady-state abundances of these radionuclides in the galaxy that are consistent with the abundances derived from meteorites, provided there is a period of free decay on the order of ~10^{8} yr prior to incorporation into the solar nebula (*Schramm and Wasserburg,* 1970; *Harper,* 1996; *Jacobsen,* 2005). Ongoing galactic nucleosynthesis might possibly contribute to ^{53}Mn, ^{107}Pd, ^{129}I, and ^{182}Hf as well. However, the levels at which the shorter-lived radionuclides ^{26}Al, ^{41}Ca, and ^{60}Fe (and probably ^{36}Cl) are maintained in the galaxy are significantly lower than those inferred from meteorites in the ESS and after a delay of ~10^{8} yr, essentially none of these radionuclides remains in the molecular cloud from which the solar system formed (*Harper,* 1996; *Wasserburg et al.,* 1996; *Meyer and Clayton,* 2000). As such, some nearby processes were creating radionuclides within ~10^{6} yr of the birth of the solar system.

It is clear that more than one process was involved since there is no proposed source that can simultaneously produce enough ^{10}Be and ^{60}Fe. Either local irradiation or trapping of GCRs might yield the observed abundance of ^{10}Be (see section 2.2), but both processes underproduce ^{60}Fe by ~3 orders of magnitude (*Lee et al.,* 1998; *Leya et al.,* 2003). Iron-60 can be produced at the levels inferred from meteorites (i.e., ^{60}Fe/^{56}Fe ratio of up to ~10^{-6}) only by stellar nucleosynthetic sources, in which beryllium is destroyed (see section 2.1.). The meteoritic data additionally suggest separate origins. Specifically, while ^{26}Al and ^{41}Ca correlate with each other in meteoritic components (*Sahijpal and Goswami,* 1998), the presence of ^{26}Al is not correlated with the presence of ^{10}Be (*Marhas et al.,* 2002). Two distinct sources are therefore required: one for ^{10}Be, and one for ^{60}Fe. However, as is evident from discussion in the previous section, some of the short-lived radionuclides, particularly ^{26}Al, ^{36}Cl, ^{41}Ca, and perhaps ^{53}Mn, could be produced by both sources. The question then is what proportions of each of these radionuclides were derived from one or the other of these sources.

The source of the ^{60}Fe was almost certainly a massive star that went supernova (i.e., Type II supernova). While other types of stellar sources could produce this isotope in sufficient abundance (Table 2), injection of material into the solar nebula by an AGB star (or a rare Type 1a supernova) is exceedingly improbable. In particular, *Kastner and Myers* (1994) quantified the spatial distribution of molecular clouds and AGB stars and estimated an upper limit to this probability of only 3×10^{-6}. At any rate, an AGB star is unlikely to produce sufficient ^{60}Fe relative to ^{26}Al (*Tachibana and Huss,* 2003). Therefore, the most plausible source of ^{60}Fe in the ESS is a Type II supernova. When that supernova injected ^{60}Fe into the material that formed the solar system, it is also likely to have injected other short-lived radionuclides such as ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn (*Meyer and Clayton,* 2000; *Goswami and Vanhala,* 2000; *Meyer,* 2005).

Therefore, while the inferred initial abundance of ^{60}Fe in the ESS places its formation near a massive star that went supernova, the timing of this event and the distance from this supernova are uncertain. The distance may have been several parsecs from the protosolar molecular cloud core and triggered its collapse (*Cameron and Truran,* 1977; *Goswami and Vanhala,* 2000; *Vanhala and Boss,* 2002). Alternatively, it may have occurred <1 pc away from the protoplanetary disk (*Chevalier,* 2000; *Ouellette et al.,* 2005). Given the extreme spatial and chemical heterogeneities of supernova ejecta, it is difficult to definitively predict the expected abundances of short-lived radionuclides that would be incorporated into the solar nebula. Nevertheless, a supernova is capable of producing all the short-lived radionuclides in the ESS (except for ^{10}Be, which has plausible alternative sources). It has been shown that injection into the protoplanetary disk of selected shells of the supernova can reproduce the inferred initial abundances of various short-lived radionuclides to within a factor of ~2 (*Meyer and Clayton,* 2000; *Meyer,* 2005; *Ouelette et al.,* 2005). Future work is clearly needed to determine the relative contributions of local production and stellar ejecta to the abundances of short-lived radionuclides, particularly ^{26}Al, ^{36}Cl, ^{41}Ca, and perhaps also ^{53}Mn.

5. FROM DUST TO PLANETESIMALS

5.1. Short-lived Radionuclides in Presolar Grains and Implications for Stellar Sources of Primordial Dust in the Solar Nebula

Since their discovery in the late 1980s, presolar grains in primitive meteorites have proven to be powerful tools for improving our understanding of stellar nucleosynthesis within and dust formation around a variety of types of stars (e.g., *Bernatowicz and Zinner,* 1997; *Nittler,* 2003; *Zinner,* 2003; *Clayton and Nittler,* 2004; *Mostefaoui and Hoppe,* 2004). These grains sample most of the types of stars that have been suggested as potential sources of short-lived isotopes in the ESS, including low-mass AGB stars and Type II supernovae. The most common types of presolar grains are diamond, silicates, silicon carbide, graphite, and the oxides corundum, hibonite, and spinel. The grain size of individual diamond grains is too small for individual isotopic analysis and even in aggregate samples, the concentrations of most elements are too low to measure. Presolar silicates have only recently been discovered (*Messenger et al.,* 2003; *Nguyen and Zinner,* 2004; *Nagashima et al.,* 2004). However, they are small (<1 μm) and the most common phases, olivine and pyroxene, do not readily take up trace elements. Most of the evidence regarding short-lived radionuclides in presolar grains comes from silicon carbide, with additional evidence from oxides and graphite. About 90% of presolar SiC grains come from low-mass AGB stars and are termed “mainstream”; 1–2%, the X-grains, have the isotopic signature of Type II supernovae. Similarly, most presolar oxides are from AGB stars and a few are from Type II supernovae.

In low-mass AGB stars, ^{12}C and *s*-process products, including some short-lived nuclides, are produced in the helium shell and periodically dredged up and mixed into the convective envelope, where they can be trapped in dust grains that form in stellar winds as the star loses mass (*Gallino et al.,* 1998; *Busso et al.,* 1999). Dust grains from AGB stars carry short-lived nuclei made throughout the AGB phase (lasting several hundred thousand years). In Type II supernovae, dust condenses from the envelope of a massive star, which is thrown off by the explosion that results from the core collapsing to a neutron star or black hole. Short-lived nuclei are made both by nuclear reactions prior to the explosion and due to the explosion itself (e.g., *Rauscher et al.,* 2002). Presolar grains from both low-mass AGB stars and Type II supernovae preserve evidence of nucleosynthesis of a number of short-lived radionuclides and we review the evidence here.

5.1.1. Sodium-22. There are two neon components highly enriched in ^{22}Ne in meteorites, Ne-E(H) and Ne-

E(L). Ne-E(H) is believed to represent the Ne-isotopic composition of the helium shells of AGB stars, implanted into mainstream presolar SiC after loss of the stellar envelope (*Gallino et al.,* 1990). Ne-E(L) is believed to be radiogenic, from the decay of ^{22}Na ($T_{1/2}$ = 2.6 yr), for which the meteoritic carrier is presolar graphite (*Amari et al.,* 1990). A significant fraction of presolar graphite is from supernovae, accounting for the preservation of Ne-E(L).

5.1.2. Aluminum-26. The presolar grain record for this radionuclide is fairly complete (*Zinner,* 2003, and references therein), as both SiC and oxides tend to have high Al/Mg ratios as well as high initial ^{26}Al/^{27}Al ratios. Mainstream SiC grains tend to have initial ratios between 10^{-4} and 10^{-3}, but a few have ratios as high as 10^{-2}. Presolar spinel, hibonite, and corundum from low-mass AGB stars formed with somewhat high ^{26}Al/^{27}Al (*Zinner et al.,* 2005). The ^{26}Al/^{27}Al ratios in mainstream SiC are similar to those predicted by AGB stellar models, but the ratios in spinel grains require an extra production process, most likely cool-bottom processing (*Zinner et al.,* 2005; *Nollett et al.,* 2003).

Most X-grains were quite ^{26}Al-rich, with initial ^{26}Al/^{27}Al ratios of 0.1–0.4. Low-density graphite grains, also believed to come from Type II supernovae, have a somewhat wider range of initial ^{26}Al/^{27}Al, from 10^{-5} to 0.2 (*Travaglio et al.,* 1999). There is abundant isotopic evidence that SiC and graphite grains do not uniformly sample the different layers of ejecta from Type II supernovae, but the levels of ^{26}Al can be explained by mixing of different layers (*Travaglio et al.,* 1999).

5.1.3. Calcium-41. Large ^{41}K excesses attributed to ^{41}Ca decay have been reported in graphite from Type II supernovae (*Travaglio et al.,* 1999) and oxide grains from low-mass AGB stars (*Nittler et al.,* 2005). The inferred ^{41}Ca/^{40}Ca ratios are 10^{-3}–10^{-2} and 10^{-5}–5×10^{-4}, respectively. Both types of stars produced ^{41}Ca by neutron capture on ^{40}Ca, in amounts consistent with those found in presolar grains.

5.1.4. Titanium-44. This isotope has a half-life of only 67 yr, yet evidence of *in situ* decay has been found in graphite and SiC from supernovae. In fact, the observed excesses in daughter ^{44}Ca are among the strongest arguments in favor of a supernova origin for these types of grains (*Amari et al.,* 1992; *Hoppe et al.,* 1996; *Travaglio et al.,* 1999; *Besmehn and Hoppe,* 2003).

5.1.5. Vanadium-49. With a half-life of only 330 d, ^{49}V holds the record for the shortest-lived extinct radionuclide for which evidence has been found in presolar grains. Excesses in daughter ^{49}Ti are correlated with V/Ti ratios in several X-type SiC grains (*Hoppe and Besmehn,* 2002), and show that grain condensation occurred within a year or so of a supernova explosion, consistent with astronomical observations of dust condensation about 500 d after the explosion of supernova 1987A (*Wooden,* 1997).

5.1.6. Zircon-93. This isotope has a half-life that is long enough (2.3 m.y.) that it behaves as if it were stable during *s*-process nucleosynthesis. It decays to monoisotopic ^{93}Nb, mostly in the ejecta of low-mass stars after the AGB phase has ended. A strong correlation between the elemental abundances of zirconium and niobium in individual presolar SiC grains measured with a synchrotron X-ray fluorescence microprobe shows that the grains condensed with live ^{93}Zr (*Kashiv et al.,* 2006).

5.1.7. Technetium-99. Technetium has no stable isotopes, but was detected in spectra of red giant stars more than 50 yr ago (*Merrill,* 1952). ^{99}Tc ($T_{1/2}$ = 213 k.y.) lies along the main *s*-process path. In fact, most ^{99}Ru is made as ^{99}Tc, which subsequently decays in AGB star envelopes or ejecta. Comparison of Ru isotope compositions of individual presolar SiC grains with models of nucleosynthesis in AGB stars show that the grains condensed with live ^{99}Tc in them (*Savina et al.,* 2004).

5.1.8. Cesium-135. Cesium is a volatile element not expected to condense into grains at high temperature, whereas barium (^{135}Cs decays to ^{135}Ba) is refractory and observed in presolar SiC. Cesium-135 ($T_{1/2}$ = 2.3 m.y.) is produced in fairly high abundance in AGB stars. Comparison of high-precision Ba isotope data on aggregates of presolar SiC (*Prombo et al.,* 1993) with stellar nucleosynthesis models strongly suggests that when the grains condensed, cesium remained in the gas (*Lugaro et al.,* 2003).

5.1.9. Outlook. There are a number of other short-lived isotopes for which records of decay could potentially be found in presolar grains from meteorites, but all are more difficult than the cases given above. Manganese-53 is only made in supernovae and there are no promising host phases for manganese. Iron-60 is made in supernovae and AGB stars and could be searched for in iron-bearing presolar silicates. Palladium-107 is made at fairly high abundance in supernovae and AGB stars, but no appropriate host exists among known types of presolar grains. Samarium-146 is made in supernovae and in small amounts in AGB stars, but presolar SiC tends to have low Sm/Nd ratios (*Yin et al.,* 2005). Hafnium-182 is also made in both supernovae and AGB stars. Hafnium as well as tungsten form carbide and are likely to be present in presolar SiC, but both are refractory and variations in Hf/W ratios are unlikely. Finally, ^{205}Pb is produced in some abundance in AGB stars, but is volatile.

5.2. Formation Timescales from Dust to Planetesimals

Evolution of the protoplanetary disk from the formation of the smallest (millimeter- to centimeter-sized) solid objects to planetary-sized bodies was long thought to be a broadly sequential process: CAIs representing the earliest material are followed by chondrules and then larger objects of asteroidal to planetary sizes. However, recent chronological studies of short-lived radionuclides and U-Pb systematics in meteorites and their components are revealing a picture that is not as orderly.

5.2.1. Formation of calcium-aluminum-rich inclusions and chondrules. The state of isotopic chronology of chondrule and CAI formation as of mid-2004 has been thoroughly reviewed by *Kita et al.* (2005) and need not be discussed here in detail. To summarize briefly, Pb-Pb systematics in CAIs from the Efremovka carbonaceous chondrite give an age of 4567.2 ± 0.6 Ma (*Amelin et al.,* 2002), which is consistent with, but more precise than, the previously determined Pb-Pb age of 4566 ± 2 Ma for Allende CAIs (*Göpel et al.,* 1994; *Allègre et al.,* 1995). This is also the oldest absolute age date for any solid formed in the solar system, and as such the CAIs are believed to be the earliest solids to form within the protoplanetary disk. Based primarily on ion microprobe analyses of ^{26}Al-^{26}Mg systematics in individual grains within CAIs and chondrules, a time difference of ~1–3 m.y. between CAI and chondrule formation has been suggested (e.g., *Kita et al.,* 2000; *Huss et al.,* 2001; *Amelin et al.,* 2002). This time difference is supported by Pb-Pb ages of CAIs from the Efremovka (reduced CV3) chondrite and chondrules from the Acfer 059 (CR) chondrite (*Amelin et al.,* 2002).

Detailed *in situ* studies (by ion microprobe or laser ablation multicollector inductively coupled plasma mass spectrometer) of ^{26}Al-^{26}Mg systematics in CAIs (e.g., *Hsu et al.,* 2000; *Young et al.,* 2005; *Taylor et al.,* 2005) suggest a prolonged residence, up to ~300,000 yr, of CAIs in the protoplanetary disk. In contrast, however, Mg-isotopic analyses of "bulk" CAIs appear to indicate that they were formed within a relatively narrow time interval of ~50,000 yr (*Bizzarro et al.,* 2004). This apparent discrepancy could be indicative of the possibility that the *in situ* and bulk analyses are recording different Al/Mg fractionation events in the history of CAI formation.

The existence of compound chondrule-CAI objects (*Krot and Keil,* 2002; *Itoh and Yurimoto,* 2003; *Krot et al.,* 2005a) indicates that chondrule formation and remelting of CAIs overlapped in time; ^{26}Al-^{26}Mg systematics in bulk chondrules from Allende further suggest that chondrules began forming contemporaneously with CAIs, and then continued to form over a time span of at least ~2–3 m.y. (*Bizzarro et al.,* 2004). Near-contemporaneous formation of at least some chondrules with CAIs is additionally supported by the Pb-Pb age of 4566.7 ± 1.0 Ma obtained for a group of Allende chondrules (*Amelin et al.,* 2004). However, as suggested by *Krot et al.* (2005a), chronologic information derived from bulk chondrules may reflect the timing of formation of chondrule precursor materials rather than the time of chondrule formation.

Chondrules from metal-rich CB carbonaceous chondrites Gujba and Hammadah al Hamra 237 have the youngest absolute age (i.e., 4562.8 ± 0.9 Ma) yet reported for chondrules from any of the unequilibrated chondrites (*Krot et al.,* 2005b). It is likely that these chondrules formed from a vapor-melt plume produced by a giant impact between planetary embryos after dust in the protoplanetary disk had largely dissipated. It is inferred from these results that planet-sized objects existed in the early asteroid belt ~4–5 m.y. after the formation of CAIs.

It has been recently shown that composition of chondrule minerals is inconsistent with crystallization from the melt under closed-system conditions, and that gas-melt interaction must have occurred during chondrule formation (*Libourel et al.,* 2005). Formation of chondrules in open-system conditions explains their compositional and structural diversity, but it also creates an additional difficulty in dating these objects. Matching the compositional variations in chondrules with their isotopic systematics will be the matter of future studies.

5.2.2. Accretion and differentiation of planetesimals. From dating of achondrites (i.e., meteorites that formed as a result of extensive melting on their parent planetesimals) using long-lived isotope chronometers, such as ^{87}Rb-^{87}Sr ($T_{1/2}$ ~ 56 G.y.) or ^{147}Sm-^{143}Nd ($T_{1/2}$ ~ 106 G.y.), it has been known for a long time that their parent bodies had undergone planet-wide melting and differentiation early in solar system history (e.g., *Lugmair,* 1974; *Allègre et al.,* 1975; *Nyquist et al.,* 1986; *Wadhwa and Lugmair,* 1995; *Kumar et al.,* 1999). However, the uncertainties of these absolute ages were too large — typically tens of millions of years — to really pin down the timescales at a desirable resolution. During the last decade or so significant advances have been made with the use of chronometers based on short-lived radionuclides toward obtaining high-resolution timescales of planetesimal melting and differentiation, which in turn have helped to place limits on the timescales required to accrete larger (tens to hundreds of kilometers in diameter) bodies from dust-sized particles. Here we will briefly summarize some of the more significant recent results bearing on the timescales of planetesimal accretion and differentiation. More detailed discussions on this topic may be found in *Nichols* (2006) and *Wadhwa et al.* (2006).

Using the ^{53}Mn-^{53}Cr system ($T_{1/2}$ = 3.7 m.y.), one of the first comprehensive studies on differentiated meteorites belonging to the howardite-eucrite-diogenite (HED) group, assumed to originate from the differentiated asteroid 4 Vesta, was published several years ago (*Lugmair and Shukolyukov,* 1998). It was shown that a planetesimal-wide differentiation caused the fractionation of Mn/Cr ratios in the mantle sources of the HED meteorites and that this episode had concluded 7.8 ± 0.8 m.y. before the formation of the LEW 86010 angrite (which serves as the time anchor for the short-lived ^{53}Mn-^{53}Cr chronometer). This translates to an age of 4564.8 ± 0.9 Ma for the conclusion of this Mn/Cr fractionation event on the HED parent body. This age can be compared with that of refractory inclusions (i.e., CAIs) found in primitive chondrites (4567.2 ± 0.6 Ma) (*Amelin et al.,* 2002), which, as discussed earlier, are believed to be the earliest condensates from the solar nebula. Considering the time difference of 2.4 ± 1.1 m.y. and the time required to assemble and melt a body the size of 4 Vesta, this clearly demonstrates that the accretion of large objects occurred at a very early time and at a very fast pace.

While both manganese and chromium are elements that mainly reside in the silicate mantle and crust of a differentiated planetesimal, they generally are not very helpful when trying to answer questions concerning silicate-metal segregation or core formation. Here a system based on another now extinct radioisotope, ^{182}Hf, that decays to ^{182}W with a half-live of 8.9 m.y., has proven to be very useful. While both elements, hafnium and tungsten, are refractory, they are strongly fractionated during silicate-metal segregation: Hafnium remains preferentially in the silicates, while tungsten partitions mainly into the metal fraction. Measuring the radiogenic contribution to ^{182}W from the decay of ^{182}Hf in the remaining tungsten in silicate samples provides information on the timing of Hf/W fractionation in the mantle, while the main Hf/W fractionation from a chondritic value may have preceded the former during core formation.

The ^{182}Hf-^{182}W system was first applied to the HED meteorites by *Quitté et al.* (2000), followed by additional analyses by *Yin et al.* (2002) and *Kleine et al.* (2004). Using the Ste. Marguerite H chondrite as the time anchor for the ^{182}Hf-^{182}W system, *Kleine et al.* (2004) obtained an age for HED parent-body mantle differentiation of 4563.2 ± 1.4 Ma, which is in agreement with the differentiation age derived from the ^{53}Mn-^{53}Cr system as discussed above. In addition, combining the HED data with ^{182}Hf-^{182}W systematics in chondrites indicates that core formation on 4 Vesta may have preceded mantle differentiation by about 1 m.y. (*Kleine et al.,* 2004).

It should be noted that the decay products of other short-lived, now extinct, radioactive isotopes have been detected in the HED meteorites and other achondrites (e.g., basaltic meteorites belonging to the angrite group) and also show their antiquity. The former presence in achondrites of live ^{26}Al ($T_{1/2}$ = 0.73 m.y.) (e.g., *Srinivasan et al.,* 1999; *Nyquist et al.,* 2003; *Baker et al.,* 2005; *Bizzarro et al.,* 2005b; *Spivak-Birndorf et al.,* 2005; *Amelin et al.,* 2006) and ^{60}Fe ($T_{1/2}$ = 1.5 Ma) (*Shukolyukov and Lugmair,* 1993a,b; *Quitté et al.,* 2005) has been clearly demonstrated. The important aspect of these findings is that both of these nuclei can serve as potent heat sources for melting and differentiation if their abundances were sufficiently high and if the meteorite parent body had accreted at a very early time. In this context, rather tight constraints on the timing of planetesimal accretion have additionally been placed by new high-precision Pb-isotopic ages of 4566.2–4566.5 Ma of recently discovered differentiated meteorites (*Baker et al.,* 2005; *Amelin et al.,* 2006), which indicate that their parent asteroids accreted and differentiated within ~1 m.y. of the formation of CAIs, essentially contemporaneously with chondrule-forming events (*Amelin et al.,* 2002, 2004). Taken together, these observations suggest that CAIs, chondrules, and differentiated asteroids formed over the same, relatively short period of time in rather complex and diverse disk environments.

One somewhat puzzling development in the last few years has resulted from a refinement of the precision of W-isotopic analyses and application to iron meteorites (some of which are thought to represent the cores of differentiated planetesimals). If differentiation and core formation on the parent planetesimals of the iron meteorites occurred during the lifetime of ^{182}Hf but after CAI formation, the expectation is that the ^{182}W/^{184}W ratios in these samples would be more radiogenic than the solar system initial value inferred from CAIs and chondrites but less radiogenic compared to bulk chondrites (i.e., between –3.5 and –2ε units relative to BSE). The earliest data on the W-isotopic compositions of iron meteorites had shown that these samples indeed have the lowest ^{182}W/^{184}W ratios of any solar system material, with values ranging from ~–3 to –5ε units relative to BSE (e.g., *Lee and Halliday,* 1995, 1996; *Horan et al.,* 1998). However, the precision of these earliest measurements was insufficient to definitively ascertain whether any of the iron meteorites had W-isotopic compositions that were resolvably lower than the initial value inferred for the solar system. More recent, higher-precision, W-isotopic analyses of iron meteorites have shown that some iron meteorites do indeed have ^{182}W/^{184}W ratios that are resolvably lower than –3.5 (*Markowski et al.,* 2006; *Kleine et al.,* 2005; *Qin et al.,* 2005). Taken at face value, this suggests that these iron meteorites formed (and that core formation on their parent planetesimals took place) earlier than CAI formation. There are, however, incompletely understood and possibly significant effects in the ^{182}Hf-^{182}W system in iron meteorites resulting from long exposure to GCRs, which may results in an apparent lowering of the measured ^{182}W/^{184}W ratios in these samples. In fact, recent results demonstrate that GCR exposure could indeed account for the least-radiogenic W-isotopic compositions in iron meteorites, but the effect on the ^{182}W/^{184}W ratio due to irradiation is unlikely to be significantly larger than ~0.5ε units (*Markowski et al.,* 2006; *Qin et al.,* 2005). As such, this leaves us with the conclusion stated earlier that formation of CAIs and chondrules on the one hand and the accretion and differentiation of planetesimals on the other occurred within a very short time span of perhaps no more than a couple of million years.

6. OUTLOOK AND FINAL REMARKS

The emerging picture of the protoplanetary disk and the potentially complex and spatially and temporally diverse environments within it leaves many open questions, and poses challenges for astronomers, astrophysicists, disk modelers, cosmochemists, and petrologists. The following are some of the topics that need more detailed exploration.

1. Because of the growing evidence that the short-lived radionuclides in the protoplanetary disk came from multiple sources, we cannot *a priori* assume homogeneous distribution for any such radionuclide in the protoplanetary disk. The relatively longer lived of these short-lived nuclides that are produced by stellar nucleosynthesis, such as ^{146}Sm, ^{244}Pu, and possibly ^{129}I and ^{182}Hf, may be mixtures of material present in the presolar molecular cloud, and freshly synthesized material injected into the disk by a nearby supernova. The presence of ^{10}Be in the ESS may be due to irradiation from the young Sun [some other short-lived radionuclides may also have been produced in this manner (*Gounelle et al.,* 2001)] and/or from trapping of GCRs in the protosolar molecular cloud (*Desch et al.,* 2004). These sources are not mutually exclusive; for example, ^{26}Al, the most widely used short-lived chronometer nuclide, can be

a mixture of material from stellar sources and irradiation mechanisms. The extent of heterogeneity in distribution of short-lived nuclides has to be evaluated by extensive comparative studies of various ESS materials: CAIs, chondrules of various origins (nebular and asteroidal/planetary), and differentiated meteorites, with a set of short-lived and long-lived (U-Pb) isotopic systems. "Mapping" an extinct-nuclide chronometer onto the absolute timescale may work for a certain nuclide in a certain group of meteorites (e.g., ^{53}Mn-^{53}Cr in the angrites and the HED meteorites) that come from a single parent asteroid or a homogeneous population of asteroids. We cannot assume, however, that the same chronometer would give compatible results for chondrules and CAIs, because short-lived radionuclides could be heterogeneously distributed at this scale (*Gounelle and Russell,* 2005a,b).

2. A related question is the timing of injection of radionuclides into the protoplanetary disk. At what point during its evolution did the disk encounter collision with the supernova ejecta? This question could potentially be addressed by establishing a correlation between (1) isotopic anomalies of nucleosynthetic origin in meteoritic components; (2) the abundances of short-lived radionuclides, e.g., ^{26}Al, ^{60}Fe, and ^{41}Ca, in these materials; and (3) their absolute ages. This may be achieved by comparative studies of U-Pb and short-lived isotopic systems in CAIs and other refractory materials (e.g., hibonite grains from CM chondrites).

3. Based on the emerging picture of early accretion (i.e., within ~1 m.y. of CAI formation) of the differentiated planetesimals, it seems plausible that the accretion of undifferentiated chondrite parent asteroids occurred late (unless such bodies were extremely small), because otherwise large asteroids would have melted as a result of heat generated by ^{26}Al and ^{60}Fe decay. How primitive materials such as presolar grains, CAIs, and chondrules could survive a few million years in the disk (i.e., until they were accreted into chondrite parent bodies) alongside the accreting and differentiating asteroids is still unclear. A better understanding of the dynamics within a protoplanetary disk would help to clarify this.

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