

# A Perspective from Extinct Radionuclides on a Young Stellar Object: The Sun and Its Accretion Disk

Nicolas Dauphas<sup>1</sup> and Marc Chaussidon<sup>2</sup>

<sup>1</sup>Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, Chicago, Illinois 60637; email: dauphas@uchicago.edu

<sup>2</sup>Centre de Recherches Pétrographiques et Géochimiques (CRPG)-Nancy Université-CNRS, UPR 2300, 54501 Vandoeuvre-lès-Nancy, France

Annu. Rev. Earth Planet. Sci. 2011. 39:351–86

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

This article's doi:

10.1146/annurev-earth-040610-133428

Copyright © 2011 by Annual Reviews.  
All rights reserved

0084-6597/11/0530-0351\$20.00

## Keywords

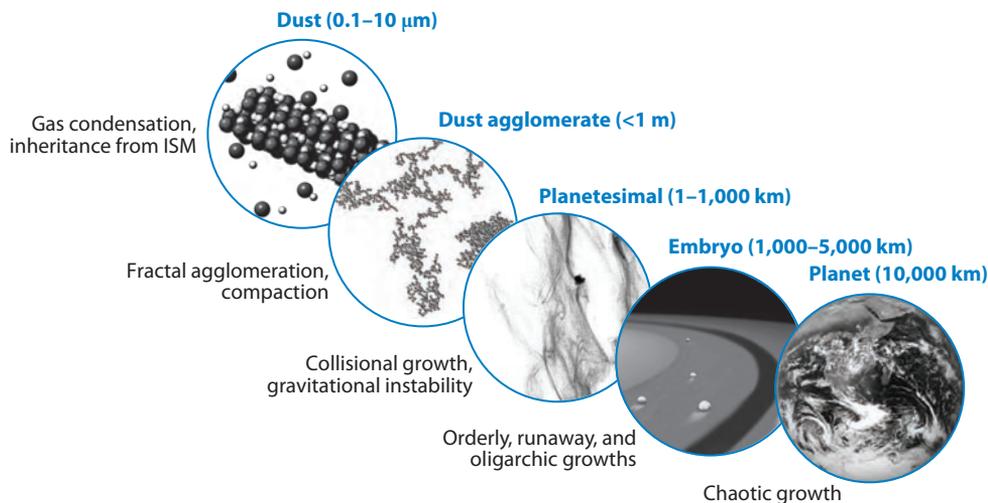
radioactivity, meteorites, solar system, chronology, irradiation

## Abstract

Meteorites, which are remnants of solar system formation, provide a direct glimpse into the dynamics and evolution of a young stellar object (YSO), namely our Sun. Much of our knowledge about the astrophysical context of the birth of the Sun, the chronology of planetary growth from micrometer-sized dust to terrestrial planets, and the activity of the young Sun comes from the study of extinct radionuclides such as <sup>26</sup>Al ( $t_{1/2} = 0.717$  Myr). Here we review how the signatures of extinct radionuclides (short-lived isotopes that were present when the solar system formed and that have now decayed below detection level) in planetary materials influence the current paradigm of solar system formation. Particular attention is given to tying meteorite measurements to remote astronomical observations of YSOs and modeling efforts. Some extinct radionuclides were inherited from the long-term chemical evolution of the Galaxy, others were injected into the solar system by a nearby supernova, and some were produced by particle irradiation from the T-Tauri Sun. The chronology inferred from extinct radionuclides reveals that dust agglomeration to form centimeter-sized particles in the inner part of the disk was very rapid (<50 kyr), planetesimal formation started early and spanned several million years, planetary embryos (possibly like Mars) were formed in a few million years, and terrestrial planets (like Earth) completed their growths several tens of million years after the birth of the Sun.

## 1. INTRODUCTION

In the past decade, considerable effort has been directed toward integrating astronomical observations of young stellar objects (YSOs), models of solar system formation, and laboratory studies of meteorites and comets to yield a general understanding of the birth of our Sun and the formation of the planets (**Figure 1**) (see also recent reviews in Davis 2005, Krot et al. 2005c, Reipurth et al. 2007). The Sun was born in a molecular cloud, probably nearby other newborn stars (Adams 2010, Lada & Lada 2003). During collapse of the solar system's parent molecular cloud core, conservation of angular momentum led to the formation of a protoplanetary disk (or proplyd), through which material accreted by the Sun was channeled. In the inner part of the disk, most material was condensed from cooling gas of near-solar composition (Grossman 1972, Grossman & Larimer 1974). The dust particles thus created, as well as those inherited from the parent molecular cloud (0.1–10  $\mu\text{m}$ ), are thought to have aggregated by Brownian motion, differential vertical settling, and turbulence (Blum & Wurm 2008, Dullemond & Dominik 2005, Weidenschilling 1980). In the size range of 10–100 cm, dust agglomerates experienced a headwind from slower-rotating gas, which led them to spiral toward the protostar (Adachi et al. 1976, Weidenschilling 1977). Possibly helped by gravitational instability in a turbulent disk (Cuzzi et al. 2008, Johansen et al. 2007), dust agglomerates coalesced into rapidly growing planetesimals (1–1,000 km in diameter)



**Figure 1**

Evolution of matter in the inner part of the solar protoplanetary disk. Solid dust was condensed from nebular gas (Grossman 1972, Grossman & Larimer 1974) and was inherited from the molecular cloud core that formed the Sun (Mathis et al. 1977, Weingartner & Draine 2001). Brownian motion, differential vertical settling, and turbulence led these particles to agglomerate into fractal agglomerates held together by van der Waals forces (Blum & Wurm 2008, Dullemond & Dominik 2005, Weidenschilling 1980). As the relative velocities of dust agglomerates increased, collisions led to compaction and eventually to fragmentation and bouncing. The size threshold above which collisions became disruptive or ineffective is <1 m. The physical process by which dust agglomerates grew into planetesimals is not well understood but could have involved gravitational instability in dust-enhanced regions of a turbulent disk (Cuzzi et al. 2008, Johansen et al. 2007). Orderly, runaway, and oligarchic growth of planetesimals formed several Moon- to Mars-sized embryos at regular heliocentric distances (Goldreich et al. 2004, Kokubo & Ida 1998, Safronov 1969, Wetherill & Stewart 1989); these embryos later collided to form terrestrial planets (Chambers & Wetherill 1998). Abbreviation: ISM, interstellar medium.

that were largely immune to the effects of a headwind known as gas drag. Models suggest that the subsequent growth of planetesimals led to the formation of several Mars-sized planetary embryos (1,000–5,000 km) regularly interspaced in heliocentric distances (Goldreich et al. 2004, Kokubo & Ida 1998, Safronov 1969, Wetherill & Stewart 1989). Collision of these embryos is believed to have led to the formation of terrestrial planets such as Earth (12,742 km) (Chambers & Wetherill 1998). At some point in this evolution, nebular gas not accreted onto the protostar was lost by photoevaporation processes (Alexander 2008, Hollenbach et al. 2000). Wind stripping from central stars probably plays a minor role in the dispersal of protoplanetary disks (Matsuyama et al. 2009).

In the present context, extinct radionuclides (**Table 1**) are defined as short-lived nuclides that were present at the time of solar system formation but have since decayed below detection level (McKeegan et al. 2006). These extinct radionuclides have diverse origins. Some, such as  $^{146}\text{Sm}$  ( $t_{1/2} = 103$  Myr), were inherited from the long-term chemical evolution of the Galaxy (Clayton 1988, Nittler & Dauphas 2006). Others, such as  $^{26}\text{Al}$  ( $t_{1/2} = 0.717$  Myr), were produced in one or several nearby stars and were mixed with solar system material shortly before formation of planetary bodies (Cameron & Truran 1977, Meyer & Clayton 2000, Takigawa et al. 2008, Wasserburg et al. 2006). A few, such as  $^{10}\text{Be}$  ( $t_{1/2} = 1.39$  Myr; Chmeleff et al. 2010), were produced by intense particle irradiation from the young Sun (Goswami et al. 2001, Gounelle et al. 2001, Leya et al. 2003, McKeegan et al. 2000). In this review, we cover how the abundance and distribution of extinct radionuclides in meteorites can be used to constrain the astrophysical setting of solar system formation, the efficiency of large-scale mixing in the protoplanetary disk, the intensity of solar flares at solar system birth, and the chronology of planetary growth and differentiation.

All lithic objects that preserve a record of extinct radionuclides derive from meteorites. Meteorites are solid remnants of the formation of the solar system and present a wide variety of characteristics, yet they are amenable to systematic classification (Krot et al. 2005b). One distinguishes, for example, between undifferentiated (unmolten) and differentiated (molten) meteorites. The unmolten meteorites are also termed chondrites because they contain chondrules, which are millimeter- to centimeter-sized, partially crystallized silicate droplets. Coexisting with these chondrules are refractory inclusions (calcium-, aluminum-rich inclusions, or CAIs) that are approximately the same size but differ in their highly refractory chemical compositions. Chondrules and CAIs are bound together by fine dust known as matrix. Although many meteorites have suffered some mineralogic alteration of their “parent bodies” (asteroids), these constituents represent a good sampling of the dust that was around in the nebula when planetary bodies formed. Differentiated meteorites were once molten and are taken to represent the mantles (achondrites) or the cores (magmatic iron meteorites) of planetesimals or planets.

The past presence of extinct radionuclides in meteorites and other solar system materials can be inferred from the study of their decay products. Thus, the past presence of the first extinct radionuclide discovered,  $^{129}\text{I}$  ( $t_{1/2} = 15.7$  Myr), was revealed through measurement of the abundance of  $^{129}\text{Xe}$  in meteorites (Jeffery & Reynolds 1961). Because of its half-life and the fact that Al can be fractionated easily from Mg by nebular and magmatic processes,  $^{26}\text{Al}$  ( $t_{1/2} = 0.717$  Myr; decays into  $^{26}\text{Mg}$ ) is more widely used to establish the chronology of solar system formation. A diagram describing its use is shown in **Figure 2**. If several rocks or minerals formed at the same time (same initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio) from homogeneous material (same initial  $^{26}\text{Mg}/^{24}\text{Mg}$  and  $^{26}\text{Al}/^{27}\text{Al}$  ratios), then Al-rich minerals such as anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) should develop more radiogenic  $^{26}\text{Mg}/^{24}\text{Mg}$  ratios compared with those of more magnesian minerals such as spinel ( $\text{MgAl}_2\text{O}_4$ ). Lee et al. (1976, 1977) used these principles to demonstrate that  $^{26}\text{Al}$  was present at the time of formation of the first solids in the solar system at a level of  $^{26}\text{Al}/^{27}\text{Al} \approx 5 \times 10^{-5}$  (see also Gray & Compston 1974). As demonstrated in this review, short-lived radionuclides such as  $^{26}\text{Al}$  and  $^{10}\text{Be}$  provide a record of the Sun as a YSO and of the evolution of its accretion disk (**Figure 3**).

**Table 1 Extinct radionuclides in meteorites**

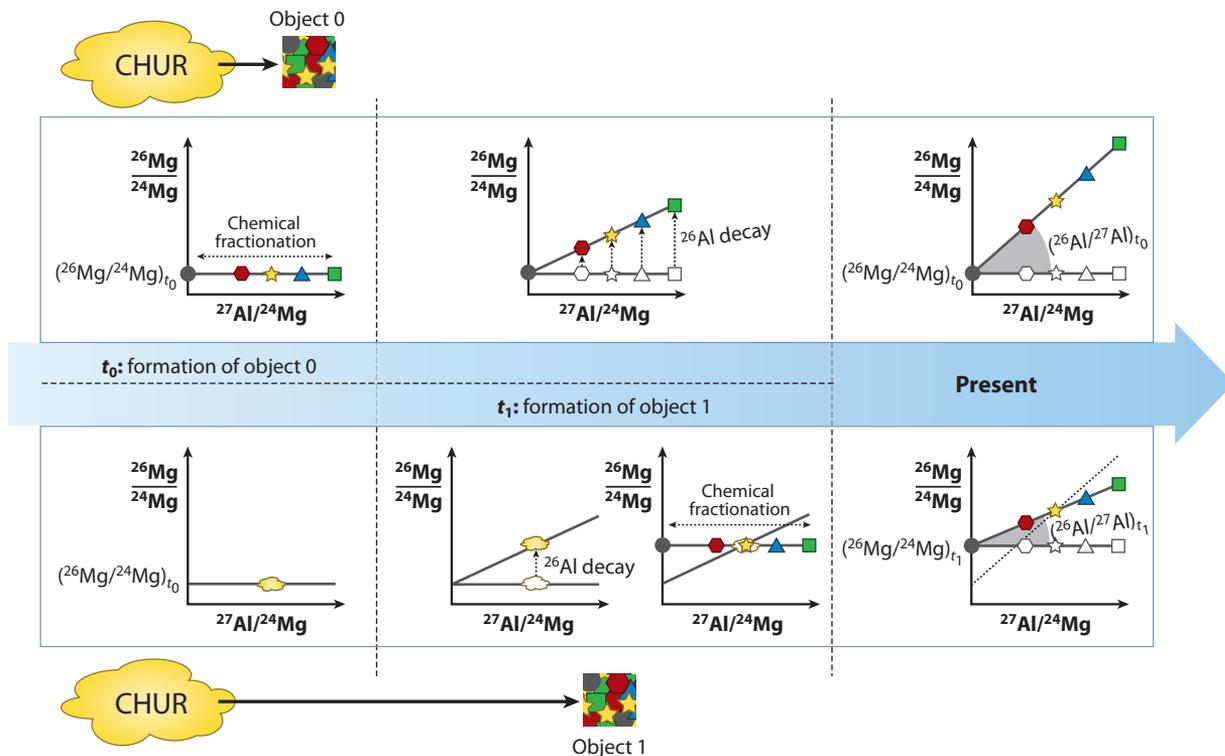
Parent nuclide	Half-life (Myr)	Decay constant (Myr <sup>-1</sup> )	Daughter nuclide	Estimated initial abundance	Note	Reference(s)
<sup>146</sup> Samarium ( <sup>146</sup> Sm)	103	0.00673	<sup>142</sup> Neodymium ( <sup>142</sup> Nd)	<sup>146</sup> Sm/ <sup>144</sup> Sm = (8.4 ± 0.5) × 10 <sup>-3</sup>	****a	Boyet et al. 2010, Lugmair & Galer 1992, Prinzhofer et al. 1992
<sup>244</sup> Plutonium ( <sup>244</sup> Pu)	80	0.0087	Fission products	<sup>244</sup> Pu/ <sup>238</sup> U = (6.8 ± 1.0) × 10 <sup>-3</sup>	***	Hudson et al. 1989
<sup>92</sup> Niobium ( <sup>92</sup> Nb)	34.7	0.0200	<sup>92</sup> Zirconium ( <sup>92</sup> Zr)	<sup>92</sup> Nb/ <sup>93</sup> Nb = (1.6 ± 0.3) × 10 <sup>-5</sup>	***	Harper 1996, Schönbächler et al. 2002
<sup>129</sup> Iodine ( <sup>129</sup> I)	15.7	0.0441	<sup>129</sup> Xenon ( <sup>129</sup> Xe)	<sup>129</sup> I/ <sup>127</sup> I = (1.19 ± 0.20) × 10 <sup>-4</sup>	***	Brazzle et al. 1999, Jeffery & Reynolds 1961
<sup>182</sup> Hafnium ( <sup>182</sup> Hf)	8.9	0.078	<sup>182</sup> Tungsten ( <sup>182</sup> W)	<sup>182</sup> Hf/ <sup>180</sup> Hf = (9.72 ± 0.44) × 10 <sup>-5</sup>	***	Burkhardt et al. 2008, Kleine et al. 2002, Yin et al. 2002
<sup>53</sup> Manganese ( <sup>53</sup> Mn)	3.74	0.185	<sup>53</sup> Chromium ( <sup>53</sup> Cr)	<sup>53</sup> Mn/ <sup>55</sup> Mn = (6.28 ± 0.66) × 10 <sup>-6</sup>	***	Birck & Allègre 1985, Shukolyukov & Lugmair 2006, Trinquier et al. 2008
<sup>10</sup> Beryllium ( <sup>10</sup> Be)	1.387	0.500	<sup>10</sup> Boron ( <sup>10</sup> B)	<sup>10</sup> Be/ <sup>9</sup> Be = (7.5 ± 2.5) × 10 <sup>-4</sup>	***	McKeegan et al. 2000; Chaussidon & Gounelle 2006, 2007
<sup>26</sup> Aluminum ( <sup>26</sup> Al)	0.717	0.967	<sup>26</sup> Magnesium ( <sup>26</sup> Mg)	<sup>26</sup> Al/ <sup>27</sup> Al = (5.23 ± 0.13) × 10 <sup>-5</sup>	***	Jacobsen et al. 2008, Lee et al. 1976
<sup>107</sup> Palladium ( <sup>107</sup> Pd)	6.5	0.11	<sup>107</sup> Silver ( <sup>107</sup> Ag)	<sup>107</sup> Pd/ <sup>108</sup> Pd = (5.9 ± 2.2) × 10 <sup>-5</sup>	**b	Chen & Wasserburg 1996, Schönbächler et al. 2008
<sup>60</sup> Iron ( <sup>60</sup> Fe)	2.62	0.265	<sup>60</sup> Nickel ( <sup>60</sup> Ni)	<sup>60</sup> Fe/ <sup>56</sup> Fe = (5.8 ± 1.3) × 10 <sup>-9</sup>	**	Quitté et al. 2010, Shukolyukov & Lugmair 1993, Tang & Dauphas 2011
<sup>36</sup> Chlorine ( <sup>36</sup> Cl)	0.301	2.30	<sup>36</sup> Sulfur ( <sup>36</sup> S) (1.9%), <sup>36</sup> Argon ( <sup>36</sup> Ar) (98.1%)	<sup>36</sup> Cl/ <sup>35</sup> Cl > (17.2 ± 2.5) × 10 <sup>-6</sup>	**	Jacobsen et al. 2009, Lin et al. 2005
<sup>247</sup> Curium ( <sup>247</sup> Cm)	15.6	0.0444	<sup>235</sup> Uranium ( <sup>235</sup> U)	<sup>247</sup> Cm/ <sup>238</sup> U = (5.5 ± 2.0) × 10 <sup>-5</sup>	*c	Brennecka et al. 2010
<sup>205</sup> Lead ( <sup>205</sup> Pb)	15.1	0.0459	<sup>205</sup> Thallium ( <sup>205</sup> Tl)	<sup>205</sup> Pb/ <sup>204</sup> Pb = (1.0 ± 0.4) × 10 <sup>-3</sup>	*	Baker et al. 2010
<sup>135</sup> Cesium ( <sup>135</sup> Cs)	2.3	0.30	<sup>135</sup> Barium ( <sup>135</sup> Ba)	<sup>135</sup> Cs/ <sup>133</sup> Cs = (4.8 ± 0.8) × 10 <sup>-4</sup>	*	Hidaka et al. 2001
<sup>41</sup> Calcium ( <sup>41</sup> Ca)	0.102	6.80	<sup>41</sup> Potassium ( <sup>41</sup> K)	<sup>41</sup> Ca/ <sup>40</sup> Ca = (1.41 ± 0.14) × 10 <sup>-8</sup>	*	Srinivasan et al. 1994, 1996
<sup>7</sup> Beryllium ( <sup>7</sup> Be)	1.46 × 10 <sup>-7</sup>	6.86 × 10 <sup>6</sup>	<sup>7</sup> Lithium ( <sup>7</sup> Li)	<sup>7</sup> Be/ <sup>9</sup> Be = 0.0061 ± 0.0013	*	Chaussidon et al. 2006
<sup>97</sup> Technetium ( <sup>97</sup> Tc)	4.21	0.16464	<sup>97</sup> Molybdenum ( <sup>97</sup> Mo)	<sup>97</sup> Tc/ <sup>92</sup> Mo < 3 × 10 <sup>-6</sup>	< <sup>d</sup>	Dauphas et al. 2002b
<sup>98</sup> Technetium ( <sup>98</sup> Tc)	4.2	0.17	<sup>98</sup> Ruthenium ( <sup>98</sup> Ru)	<sup>98</sup> Tc/ <sup>96</sup> Ru < 2 × 10 <sup>-5</sup>	<	Becker & Walker 2003
<sup>126</sup> Tin ( <sup>126</sup> Sn)	0.23	3.0	<sup>126</sup> Tellurium ( <sup>126</sup> Te)	<sup>126</sup> Sn/ <sup>124</sup> Sn < 7.7 × 10 <sup>-5</sup>	<	Fehr et al. 2006

<sup>a</sup>The \*\*\* symbol means that the extinct radionuclide was present when the solar system formed and that its initial abundance has been precisely determined in some primitive components of meteorites.

<sup>b</sup>\*\* means that there is convincing evidence for the presence of the extinct radionuclide but that its initial abundance is uncertain.

<sup>c</sup>\* means that there are reports of the extinct radionuclide in meteorites but that the evidence is weak and awaits confirmation.

<sup>d</sup>< means that the extinct radionuclide has not been detected (only an upper limit on its initial abundance exists).



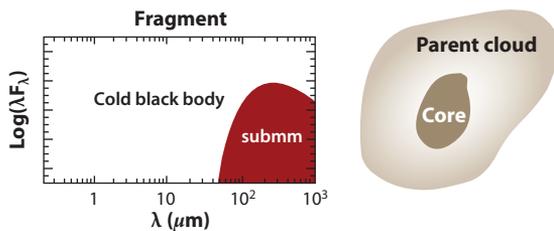
**Figure 2**

Principles behind the use of the  $^{26}\text{Al}$ - $^{26}\text{Mg}$  decay system in meteorites ( $t_{1/2} = 0.717$  Myr). Until an object forms, the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio evolves in a reservoir of chondritic  $^{27}\text{Al}/^{24}\text{Mg}$  ratio (chondritic uniform reservoir, or CHUR). When object 0 forms at  $t_0$ , partitioning of Al and Mg between several phases fractionates the  $^{27}\text{Al}/^{24}\text{Mg}$  ratio. After decay of  $^{26}\text{Al}$  in that object, the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio must correlate with the  $^{27}\text{Al}/^{24}\text{Mg}$  ratio according to the equation (Lee et al. 1976, 1977)  $(^{26}\text{Mg}/^{24}\text{Mg})_{\text{measured at present}} = (^{26}\text{Mg}/^{24}\text{Mg})_{\text{initial}} + (^{26}\text{Al}/^{27}\text{Al})_{\text{initial}} \times (^{27}\text{Al}/^{24}\text{Mg})_{\text{measured at present}}$ . The slope of the correlation gives the  $^{26}\text{Al}/^{27}\text{Al}$  ratio at  $t_0$ , whereas the intercept gives the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio at  $t_0$ . When object 1 forms at  $t_1$ , the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio in CHUR increases owing to decay of  $^{26}\text{Al}$ . The measured correlation between  $^{26}\text{Mg}/^{24}\text{Mg}$  and  $^{27}\text{Al}/^{24}\text{Mg}$  in object 1 should therefore have lower slope (lower initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio) and higher intercept (higher initial  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio) than those measured in object 0. The time difference between formation of objects 0 and 1 is given by  $t_1 - t_0 = (1/\lambda_{^{26}\text{Al}}) \times \ln[(^{26}\text{Al}/^{27}\text{Al})_{t_0}/(^{26}\text{Al}/^{27}\text{Al})_{t_1}]$ . In isochron diagrams,  $\delta^{26}\text{Mg}^* = [(^{26}\text{Mg}/^{24}\text{Mg})_{\text{sample}}/(^{26}\text{Mg}/^{24}\text{Mg})_{\text{CHUR}} - 1] \times 10^3$  is used in place of the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio. This is only a matter of convenience. It is, for example, easier to report that a sample has excess  $\delta^{26}\text{Mg}^*$  of 1‰ relative to CHUR rather than to report two  $^{26}\text{Mg}/^{24}\text{Mg}$  isotopic ratios of 0.13946 and 0.13932 for the sample and CHUR, respectively. The relationship between  $\delta^{26}\text{Mg}^*$  and the  $^{27}\text{Al}/^{24}\text{Mg}$  ratio takes the form  $\delta^{26}\text{Mg}^*_{\text{measured at present}} = \delta^{26}\text{Mg}^*_{\text{initial}} + (^{26}\text{Al}/^{27}\text{Al})_{\text{initial}} \times (^{27}\text{Al}/^{24}\text{Mg})_{\text{measured at present}} \times (^{24}\text{Mg}/^{26}\text{Mg})_{\text{CHUR}} \times 10^3$ .

## 2. THE ASTROPHYSICAL CONTEXT OF SOLAR SYSTEM FORMATION AND THE EFFICIENCY OF MIXING

Whereas many extinct radionuclides were inherited from the long-term chemical evolution of the Galaxy (Clayton 1988, Nittler & Dauphas 2006), the ones with half-lives of less than a few million years (e.g.,  $^{26}\text{Al}$ ,  $^{41}\text{Ca}$ ,  $^{53}\text{Mn}$ , and  $^{60}\text{Fe}$ ) can potentially tie the forming solar system to its immediate astrophysical environment (Adams 2010). Soon after the discovery of  $^{26}\text{Al}$  (Lee et al. 1976), this nuclide was proposed to be the signature of the explosion of a core-collapse (type II) supernova that would have triggered the collapse of the molecular cloud core that made the Sun (Cameron & Truran 1977). Indeed, its initial abundance ( $^{26}\text{Al}/^{27}\text{Al} = 5.23 \pm 0.13 \times 10^{-5}$ ; Jacobsen

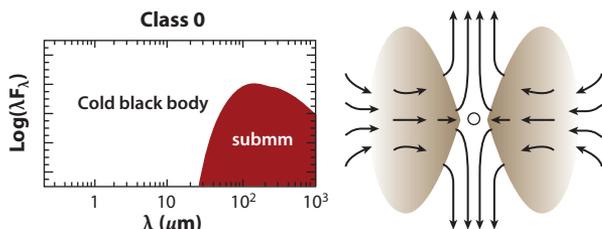
**Prestellar phase**



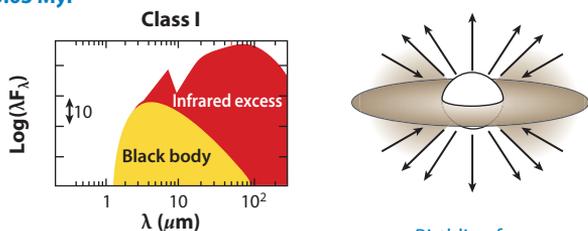
Formation of the central protostellar object

$t = 0$

**Protostellar phase**



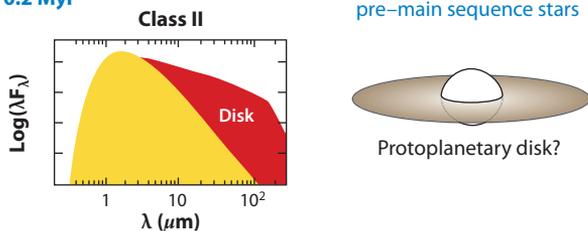
$t < 0.03$  Myr



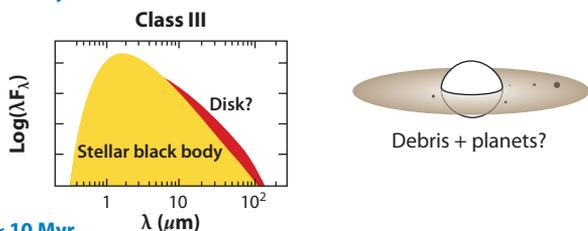
$t \approx 0.2$  Myr

Birthline for pre-main sequence stars

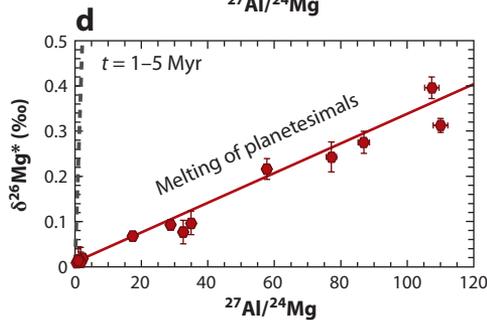
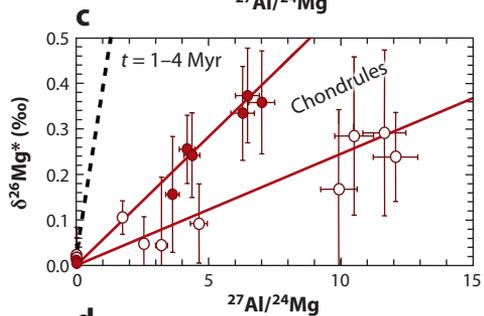
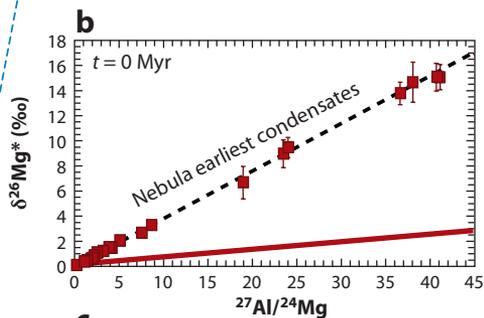
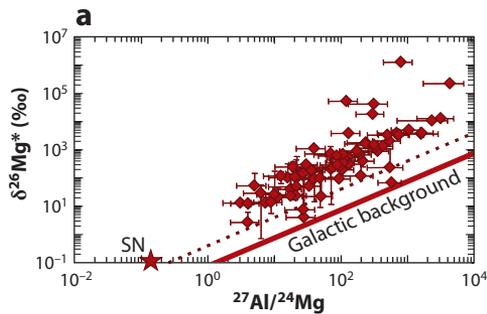
**Pre-main sequence phase**



$t \approx 1$  Myr



$t \approx 10$  Myr



et al. 2008) is approximately one order of magnitude higher than that of the galactic background ( $8.4 \pm 2.4 \times 10^{-6}$ ; Diehl et al. 2006). From the observation of additional extinct radionuclides, this idea was refined to suggest that the forming solar system was polluted by  $\sim 10^{-4}$  solar mass of freshly nucleosynthesized matter from the outflow of a supernova that exploded  $\sim 1$  Myr before solar system formation (e.g., Birck & Allègre 1988, Meyer & Clayton 2000, Takigawa et al. 2008, Wasserburg 1987). Another possible scenario is that the solar system was contaminated by the wind from a nearby asymptotic giant branch (AGB) star (see Wasserburg et al. 2006 and references therein). However, the probability of having an AGB star at the time and place of the formation of the solar system is small (Kastner & Myers 1994). Indeed, AGB stars are evolved stars, and their presence in star-forming regions would be coincidental. Conversely, core-collapse supernovae are expected to be present in stellar nurseries. The constraints that can be brought from extinct radionuclides on the putative astrophysical sources are highly dependent on initial solar system abundances. In particular, a high initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio would be indicative of a supernova origin for some (Wasserburg et al. 1998). One difficulty with  $^{60}\text{Fe}$  comes from the fact that it has not been detected in refractory inclusions because of the presence of Ni nucleosynthetic anomalies (Birck & Lugmair 1988, Quitté et al. 2007), and it was identified only in objects formed later. Taken at face value, measurements reported in the literature are contradictory. Measurements of bulk angrites and eucrites (meteorites representing fragments of the mantles of differentiated planetesimals) define an initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of  $(5.8 \pm 1.3) \times 10^{-9}$  when back-calculated to the time of CAI formation (Quitté et al. 2010, Tang & Dauphas 2011), whereas chondrules give an initial ratio of  $(4.3 \pm 1.4) \times 10^{-7}$  at the time of CAI formation (Mishra et al. 2010, Tachibana et al. 2006). Both values were calculated with the same half-life for  $^{60}\text{Fe}$  of 2.62 Myr (Rugel et al. 2009). Further work will be required to assess which of these values corresponds to the initial solar system abundance. Until this is done, constraints put on the astrophysical context of solar

### Figure 3

$^{26}\text{Al}$  record of solar system formation anchored to astrophysical observations of nascent stars (adapted from André 2002). (Left) The five different stages, from prestellar core to class 0–III stellar sources, are identified from the observed infrared excess relative to a blackbody spectrum. Observations of young stellar objects (YSOs) show that the duration from class 0 to class III is at most  $\sim 10$  Myr (André 2002, Cieza et al. 2007, Montmerle et al. 2006, Reipurth 2005). (Right)  $^{26}\text{Al}$  variations in meteoritic components provide a way to define independently a similar timescale for the young Sun, which can be followed by the variations of the  $^{26}\text{Al}/^{27}\text{Al}$  ratio (i.e., the slopes of the  $^{26}\text{Al}$  isochrons shown in the panels a–d). Panel a shows an image, although strongly biased, of the isotopic heterogeneity (fossil excesses of  $^{26}\text{Al}$ ) carried by grains present in the parent cloud. Red dots correspond to a subset of SiC presolar grains from the Orgueil chondrite (Huss et al. 1997). The  $^{26}\text{Al}$  galactic background (Diehl et al. 2006) is shown by a thick line in panels a and b. The star in panel a corresponds to the possible composition of the accretion disk characterized by a  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5 \times 10^{-5}$  after injection of Al and Mg isotopes from a nearby supernova (SN). Panel b shows time zero for  $^{26}\text{Al}$  chronology, which can be defined by the formation of calcium-, aluminum-rich inclusions (CAIs) from CV chondrites (a class of CAI-rich carbonaceous chondrites that are named after the Vigarano meteorite). This happened when  $^{26}\text{Al}/^{27}\text{Al}$  was homogenized to  $5.2 \times 10^{-5}$  in the inner solar system (Bouvier & Wadhwa 2010, Jacobsen et al. 2008, MacPherson et al. 2010a,b). The presence in these CAIs of short-lived  $^{10}\text{Be}$  made by irradiation from the young active Sun links this “age zero” to the Sun when it was a class II (active T-Tauri) star (or perhaps even a class I star). This means that, in theory, meteorites might contain older (by up to a few hundred thousand years at most) components. Accretion processes in the disk were coeval with the formation of CAIs and led to the rapid formation of the first generation of planetesimals, as shown by short-lived  $^{182}\text{Hf}$  in some magmatic iron meteorites. Panel c shows the formation times of two chondrules (open and solid dots) from the Semarkona chondrite characterized by  $^{26}\text{Al}/^{27}\text{Al}$  ratios of  $7.9 \times 10^{-6}$  and  $3.4 \times 10^{-6}$  (data from Villeneuve et al. 2009). Chondrules were formed by high-temperature processes in the disk over a time interval of  $\sim 1$  to 4 Myr after CAIs. Panel d shows the melting age of the parent body of angrites, a class of differentiated meteorites. The data define an isochron with a slope corresponding to an initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5.1 \times 10^{-7}$  (Schiller et al. 2010, Spivak-Birndorf et al. 2009), i.e., a melting age of  $\sim 5$  Myr after CAIs. The angrite parent body must have accreted  $\sim 2$  Myr earlier. The earlier accretion of the parent bodies of some magmatic iron meteorites cannot be dated with  $^{26}\text{Al}$ . Planetesimals and planetary embryos (the size of Mars or Mars itself) were presumably formed when the Sun was still a T-Tauri star.

system formation from  $^{60}\text{Fe}$  should be taken with a grain of salt. The proposed values for the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio in meteorites encompass the  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of  $1.4 \pm 0.9 \times 10^{-7}$  that can be calculated from analysis of  $\gamma$ -ray emission from the galactic plane ( $^{60}\text{Fe}/^{26}\text{Al} = 0.148 \pm 0.06$ ; Wang et al. 2007), and an enhancement of this galactic background by a factor of 2 at 4.5 Gyr is possible (Williams 2010).

Theoretical considerations and observations demonstrate the feasibility of triggering the formation of the solar system by an interstellar shock wave propagating from a supernova on a molecular cloud core (Vanhala & Boss 2002), although a restricted range of conditions (supernova distance, shock-wave velocity) is required (Boss et al. 2008). Alternatively, in case of direct injection from a massive star going supernova near an already formed protoplanetary disk, the disk can survive the flash of ultraviolet radiation from the supernova, the ram pressure (drag force exerted by the ejecta on the disk), and the input of momentum caused by the supernova shock (Ouellette et al. 2005, 2007). In such a scenario, numerical simulations show that the efficiency of injection into the protoplanetary disk should be very low ( $\sim 1\%$ ) for the gas phase but might be near 100% for solid grains condensed in the ejecta, which could be the carriers of some extinct radionuclides (Ouellette et al. 2007). The presence, in the right amount, of  $^{60}\text{Fe}$  and  $^{26}\text{Al}$  in the solar system's parental molecular cloud can also be viewed as the contribution from numerous supernovae enriching the parcel of gas and dust that made the Sun over a period of  $\sim 20$  Myr (Gounelle et al. 2009). Thus, there are several solutions to the stellar origin of extinct radionuclides with very short half-lives, but the uncertainties associated with model predictions or with initial abundance determinations from meteorites do not allow us to favor definitely one scenario over another.

Extinct radionuclide abundances in meteorites more usefully constrain mixing processes between the stellar ejecta and the accretion disk. Recently, evidence has been found for a relatively homogeneous distribution (at the  $\pm 10\%$  level) of  $^{26}\text{Al}$  (Villeneuve et al. 2009). The fundamental difficulty in establishing the homogeneity of  $^{26}\text{Al}$  is that comparing the  $^{26}\text{Al}/^{27}\text{Al}$  measured in different objects requires that their absolute ages must be determined precisely and independently to correct for rapid  $^{26}\text{Al}$  decay. One way to circumvent this difficulty is to compare the  $\delta^{26}\text{Mg}^*$  values of objects that have different  $^{26}\text{Al}/^{27}\text{Al}$  ratios ( $\delta^{26}\text{Mg}^*$  is the radiogenic excess in the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio in parts per thousand, defined as  $\delta^{26}\text{Mg}^* = [(^{26}\text{Mg}/^{24}\text{Mg})_{\text{sample}} / (^{26}\text{Mg}/^{24}\text{Mg})_{\text{CHUR}} - 1] \times 10^3$ ). In the case of initially homogeneous Mg and Al isotopes in a reservoir of constant Al/Mg ratio (assumed to be solar or chondritic for the accretion disk), their  $\delta^{26}\text{Mg}^*$  values should increase proportionally to the decrease of their  $^{26}\text{Al}/^{27}\text{Al}$  ratios (compare the intercepts and slopes of the present isochrons in **Figure 2**). This effect is small (a  $\sim 0.03\%$  increase of the  $\delta^{26}\text{Mg}^*$  value for complete  $^{26}\text{Al}$  decay from  $^{26}\text{Al}/^{27}\text{Al} = 5.2 \times 10^{-5}$  to 0), but it was demonstrated to be present among chondrules, Earth, and CAIs, thanks to the development of high-precision in situ analyses (Villeneuve et al. 2009). This result constrains Mg and Al isotopes to a homogeneous distribution of  $\pm 10\%$  relative to the average in those three reservoirs (Villeneuve et al. 2009). Similarly, high-precision Ni isotope analyses have shown that early-formed magmatic iron meteorites (see Section 5) have no  $^{60}\text{Ni}$  deficits (and collateral anomalies on  $^{58}\text{Fe}$  and  $^{64}\text{Ni}$ ) relative to chondrites, as would be expected if they formed either prior to the injection of  $^{60}\text{Fe}$  or in zones of the accretion disk devoid of  $^{60}\text{Fe}$  (Dauphas et al. 2008). This suggests that the initial  $^{60}\text{Fe}$  was homogeneously distributed at the  $\pm 10\%$  level, but a definitive conclusion on this issue awaits redetermination of the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio in chondrites. Numerical simulations (Boss 2007) indicate that extinct radionuclides (e.g.,  $^{26}\text{Al}$ ) injected at the surface of the nebula will be homogenized down to  $\pm 10\%$  in a few thousand years (at least at the scale of the grid resolution used in these simulations), in agreement with the meteoritic record. The results presented here do not prevent the presence of some heterogeneity for some extinct radionuclides at a fine scale. For example, FUN inclusions

(FUN is an acronym that refers to the isotope fractionation and unknown nuclear effects measured in these inclusions, which distinguishes them from normal CAIs; Clayton & Mayeda 1977, Wasserburg et al. 1977) and some hibonite inclusions do not show evidence of the presence of  $^{26}\text{Al}$  (MacPherson et al. 1995, Liu et al. 2009), presumably because they formed early, before complete homogenization of this extinct radionuclide occurred. A CAI from a comet yielded no detectable trace of  $^{26}\text{Al}$  (i.e.,  $^{26}\text{Al}/^{27}\text{Al} < 10^{-5}$ ; Matzel et al. 2010), and further work should tell whether this is due to formation before  $^{26}\text{Al}$  homogenization or formation/resetting after  $^{26}\text{Al}$  decay.

Finally, in a rather counterintuitive way, such rapid mixing processes may also explain the presence of large-scale isotopic heterogeneities in the accretion disk that are known to be present at planetary scales for either major (oxygen; Clayton 2007, Clayton et al. 1973) or trace (molybdenum; Dauphas et al. 2002b) elements. Indeed, such processes could reveal isotopic anomalies from a globally homogeneous medium by aerodynamically sorting the grains in size, if grains of a certain dimension were to carry the isotopic anomalies. This idea was proposed to explain  $^{54}\text{Cr}$  variations measured in bulk planetary materials because the carrier of these anomalies is very fine grained (<100 nm); it would follow the gas and thus be decoupled easily from coarser grains (Dauphas et al. 2010).

### 3. IRRADIATION

Studies of the X-ray activity of low-mass, pre-main sequence stars have revealed that these stars show time-averaged luminosity and power of individual flares that exceed present-day solar values by several orders of magnitude (Feigelson & Montmerle 1999, Feigelson et al. 2002). Although the origin of this strong X-ray activity is incompletely understood, observations of well-characterized T-Tauri stars in the Orion nebular cluster made using the Chandra Orion Ultradeep Project (COUP) indicate that it probably arises from a turbulent dynamo created in the depths of the stellar convection zone, if the T-Tauri stars are fully convective (Preibisch et al. 2005). Alternatively, if the T-Tauri stars are not fully convective, their X-ray activity must result from a solar-like dynamo operating at the base of their convection zones. Energy released during accretion shocks and/or periodical reconnections of the dipolar stellar magnetic field due to differential rotation of the star and the accretion disk, whose inner part is connected to the stellar magnetic field, can heat the gas surrounding the star to X-ray-emitting temperatures (more than  $10^7$  K) (Preibisch et al. 2005). Regardless of these uncertainties, it is obvious that circumstellar material around an X-ray-emitting T-Tauri star must be partly photoionized, which should influence accretion and outflow processes as well. COUP observations in the Orion nebula cluster show that the X-ray luminosity ( $L_X$ ) of a T-Tauri star depends on its mass and age, with an average value of  $\log(L_X) = 30.37 \pm 0.07$  ergs  $\text{s}^{-1}$  for  $1 M_\odot$  (solar mass) and 1 Myr—i.e.,  $\sim 3$  orders of magnitude higher than the X-ray luminosity of the contemporary Sun (Preibisch et al. 2005). For pre-main sequence stars in the age range of 0.1–10 Myr and the solar mass range of  $0.1 < M < 2 M_\odot$ , the luminosity decreases slightly with stellar age according to  $L_X \propto t^{-1/3}$ , whereas the decrease is more rapid over longer timescales (Preibisch & Feigelson 2005). This implies that a solar mass star can be considered active for X-ray emission during the first  $\sim 10$  Myr of its life.

Given astronomical observations of YSOs, it is difficult to imagine how the young Sun could have escaped such enhanced X-ray activity. The question, however, is to know whether this could have left traces in material that is now in the inner part of the solar system. The X-ray luminosity is the sign of enhanced luminosity at all wavelengths, but it is also accompanied by an enhanced emission of protons,  $\alpha$  particles, and  $^3\text{He}$  nuclei to energies of 1 MeV per nucleon and higher. The proton luminosity  $L_p$  for particles with energies higher than 10 MeV can be scaled to  $L_X$  using observations in present-day solar flares according to  $L_p (E \geq E_{10}) \approx 0.09 \times L_X$  (Lee et al.

1998). Interactions of these accelerated particles with ambient gas and grains result in nuclear reactions that can theoretically produce a wealth of nuclei, including short-lived radionuclides. Although extinct radionuclides are the topic of this review, it is important to stress that the potential production of some short-lived radionuclides in the accretion disk is only one of the fundamental consequences of an early active Sun (see review by Chaussidon & Gounelle 2006). Irradiation by ultraviolet light could be of key importance to other processes. Self-shielding of ultraviolet light by CO gas (Clayton 2002) was, for instance, one of the mechanisms considered to explain the presence of non-mass-dependent oxygen isotope variations in solar system objects. Extreme ultraviolet light from the T-Tauri Sun was also suggested to be responsible for hydrodynamic escape of the atmosphere from the young forming Earth (Dauphas 2003, Hunten et al. 1987, Pepin 1991, Sekiya et al. 1980).

The finding of short-lived  $^{10}\text{Be}$  ( $t_{1/2} = 1.39$  Myr), in the form of  $^{10}\text{B}$  excesses in a CAI corresponding to  $^{10}\text{Be}/^9\text{Be} = 8.8 \pm 0.6 \times 10^{-4}$  (McKeegan et al. 2000), is proof that irradiation occurred and left traces in solar system material, as this nuclide cannot be produced by other processes. In the same inclusion, large  $^7\text{Li}$  excesses also were detected, which can be explained by the in situ decay of short-lived  $^7\text{Be}$  ( $t_{1/2} = 53$  days) with  $^7\text{Be}/^9\text{Be} = 6.1 \pm 1.6 \times 10^{-3}$  at the time of crystallization of the CAI (Chaussidon et al. 2006). Because of its extremely short half-life and the complex geochemical behavior of daughter  $^7\text{Li}$ , identification of  $^7\text{Be}$  in CAIs is not definitive, and further work will be required to ascertain its presence in the early solar system. Li-Be-B elements are not produced in significant amounts by Big Bang nucleosynthesis or stellar nucleosynthesis but instead result from spallation reactions between galactic cosmic-ray protons and O and C nuclei in the interstellar medium. As a consequence, their cosmic abundances are  $\sim 10^6$ – $10^9$  times lower than those of neighboring light elements, which makes them sensitive to production through spallation reactions by early solar cosmic rays (Reeves 1994, Reeves et al. 1970). Beryllium-10 is widespread in refractory phases (in hibonites and various types of refractory inclusions) formed early in the solar disk, with  $^{10}\text{Be}/^9\text{Be}$  ratios ranging from  $\sim 3 \times 10^{-4}$  to  $\sim 1.8 \times 10^{-3}$  (Liu et al. 2009, 2010; MacPherson et al. 2003; Marhas et al. 2002; McKeegan et al. 2000; Sugiura et al. 2001). The former presence of  $^{10}\text{Be}$  has not been demonstrated in chondrules, probably because of low Be/B fractionation, but investigators have found large Li and B isotopic variations that likely result from the addition of spallogenic Li and B produced together with  $^{10}\text{Be}$  (and  $^7\text{Be}$ ) (Chaussidon & Robert 1995, 1998). Similarly,  $^{21}\text{Ne}$  cosmogenic excesses attributed to early solar system irradiation processes have long been known in olivines (a ferromagnesian silicate) from different meteorites (Caffee et al. 1987, Hohenberg et al. 1990), and their presence recently has been established in meteoritic chondrules (Das et al. 2010).

In addition to the case for  $^{10}\text{Be}$ , the case for an irradiation origin of short-lived  $^{36}\text{Cl}$  ( $t_{1/2} = 0.3$  Myr) is also strong. This is because the initial  $^{36}\text{Cl}/^{35}\text{Cl}$  ratio inferred to explain the  $^{36}\text{S}$  excesses found in late-stage alteration products of CAIs exceeds  $\sim 10^{-4}$ , which is too high to be accounted for by any stellar source (Hsu et al. 2006, Jacobsen et al. 2009, Lin et al. 2005). The situation is less clear for  $^{26}\text{Al}$ ,  $^{41}\text{Ca}$ , and  $^{53}\text{Mn}$ , although an irradiation origin of  $^{26}\text{Al}$  was considered a possibility when it was discovered (Heymann & Dziczkaniec 1976; Lee et al. 1976, 1977). Different calculations have been performed assuming various irradiation scenarios, either at asteroidal distances assuming no shielding by nebular gas (Goswami et al. 2001, Marhas et al. 2002) or at distances close to the Sun (Gounelle et al. 2001, 2006; Leya et al. 2003) in the framework of the X-wind model. In this model, proto-CAIs are irradiated in the reconnection ring at the inner edge of the accretion disk before being launched to asteroidal distances by a magnetocentrifugal outflow known as the X-wind (Shu et al. 1996, 2001). Although these calculations differ in their results because of the uncertainty in the parameters considered (e.g., fluence, composition of the target), they agree on the general picture that whereas  $^{36}\text{Cl}$ ,  $^{53}\text{Mn}$ , and  $^{41}\text{Ca}$  can be produced together with

$^{10}\text{Be}$  at their meteoritic abundances,  $^{26}\text{Al}$  is generally underproduced by a factor of 2–5 unless specific conditions are assumed (e.g.,  $^3\text{He}$ -rich impulsive flares). This factor holds if no limitation is considered in the total energy available for irradiation or in the total mass of irradiated material. In consideration of such limitations, the conclusion is that although irradiation must contribute locally to the budget of early solar system  $^{26}\text{Al}$ , it is probably a minor component in the overall disk inventory. First,  $^{26}\text{Al}$  and  $^{10}\text{Be}$  do not correlate in hibonites and CAIs (Chaussidon & Gounelle 2006, Marhas et al. 2002, Liu et al. 2009). Second, the systematics of the Mg isotopic composition of Earth, chondrules, and CAIs implies that  $^{26}\text{Al}$  was homogeneously distributed (at the  $\pm 10\%$  level) in the accretion disk at the time of formation of type B (once-molten, coarse-grained) CAIs (Villeneuve et al. 2009). This observation is difficult to reconcile with a local irradiation scenario. Finally, energetic constraints obtained from the observations of YSOs limit the amount of  $^{26}\text{Al}$  that could have been produced by irradiation (Duprat & Tatischeff 2007, 2008). A homogeneous distribution of  $^{10}\text{Be}$  and  $^{26}\text{Al}$  in the accretion disk implies the production of  $3 \times 10^{-8} M_{\oplus}$  (Earth mass) of  $^{10}\text{Be}$  and  $7 \times 10^{-4} M_{\oplus}$  of  $^{26}\text{Al}$ . This is the most conservative estimate made for a disk with a mass of  $0.5 M_{\odot}$ , a dust/gas ratio of  $10^{-2}$ , a  $^{10}\text{Be}/^9\text{Be}$  ratio of  $10^{-3}$ , a  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5 \times 10^{-5}$ , and Be and Al in solar or chondritic concentrations. If irradiation of solids close to the Sun is assumed (the most favorable case with no shielding of protons), the required amount of  $^{10}\text{Be}$  is obtained for a 10-MeV proton fluence of  $4.3 \times 10^{43}$  erg, which corresponds to 3 Myr of irradiation around a young Sun with an X-ray luminosity of  $5 \times 10^{23} \text{ J s}^{-1}$  ( $10^3$  times that of the present-day Sun). Under these conditions, the amount of  $^{26}\text{Al}$  produced is  $\sim 500$  times lower than the required amount (Duprat & Tatischeff 2007, 2008). If irradiation products were not distributed homogeneously in the entire disk but just in  $80 M_{\oplus}$ , i.e., in the portion of the disk corresponding to the rocky component of a minimum-mass solar nebula, the irradiation time required to make the correct amount of  $^{10}\text{Be}$  is reduced from 3 to 0.15 Myr. However,  $^{26}\text{Al}$  is still underproduced by a factor of  $\sim 25$  if it is to make  $80 M_{\oplus}$  of chondrites with  $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ .

The presence of  $^{10}\text{Be}$  in the refractory components of chondrites (CAIs, hibonites) anchors the formation of these minerals formed by condensation from the hot ( $>1500 \text{ K}$ ) nebula gas to the pre-main sequence evolution of the Sun (the T-Tauri phase shown in **Figure 3**). The variations in  $^{10}\text{Be}/^9\text{Be}$  observed between some igneous refractory inclusions ( $8.8 \pm 0.6 \times 10^{-4}$ ) and more refractory hibonite grains ( $5.3 \pm 1.0 \times 10^{-4}$ )—which, taken at face value, would indicate hibonites to be  $\sim 1.1$  Myr younger than some CAIs—probably do not indicate time differences. Instead, the variations likely reflect heterogeneities in the distribution of  $^{10}\text{Be}$ , in agreement with irradiation processes taking place during short and repetitive flare events (Liu et al. 2009). The presence of irradiation products (cosmogenic Li, B, and  $^{21}\text{Ne}$ ) in chondrules that are between  $\sim 1.2$  and  $\sim 4$  Myr younger than CAIs (Kita et al. 2005a, Villeneuve et al. 2009) is consistent with the expected duration of the pre-main sequence phase of the Sun.

#### 4. TIME ZERO, DUST CONDENSATION, AND AGGLOMERATION

Most primitive meteorites contain refractory inclusions several tens of micrometers to a few centimeters in size that have ceramic-like mineralogy and chemistry (Christophe Michel-Lévy 1968, Grossman 1972, MacPherson 2005). Equilibrium thermodynamic calculations show that the chemical compositions of these CAIs are consistent with high-temperature condensation ( $\sim 1,300$  to  $1,500 \text{ K}$ , depending on the total pressure) from a gas of solar composition (Grossman 1972, Grossman et al. 2000). CAIs must have formed early and close to the Sun (e.g.,  $<2$  Myr after formation of the Sun and  $\ll 2 \text{ AU}$ ), when and where the temperatures were sufficiently high for the most refractory elements to be in the gas phase (Boss 1998, Ciesla 2010, D'Alessio et al. 2005, Makalkin & Dorofeeva 2009). These products of inner solar system chemistry can be found in

kyr: thousands of years

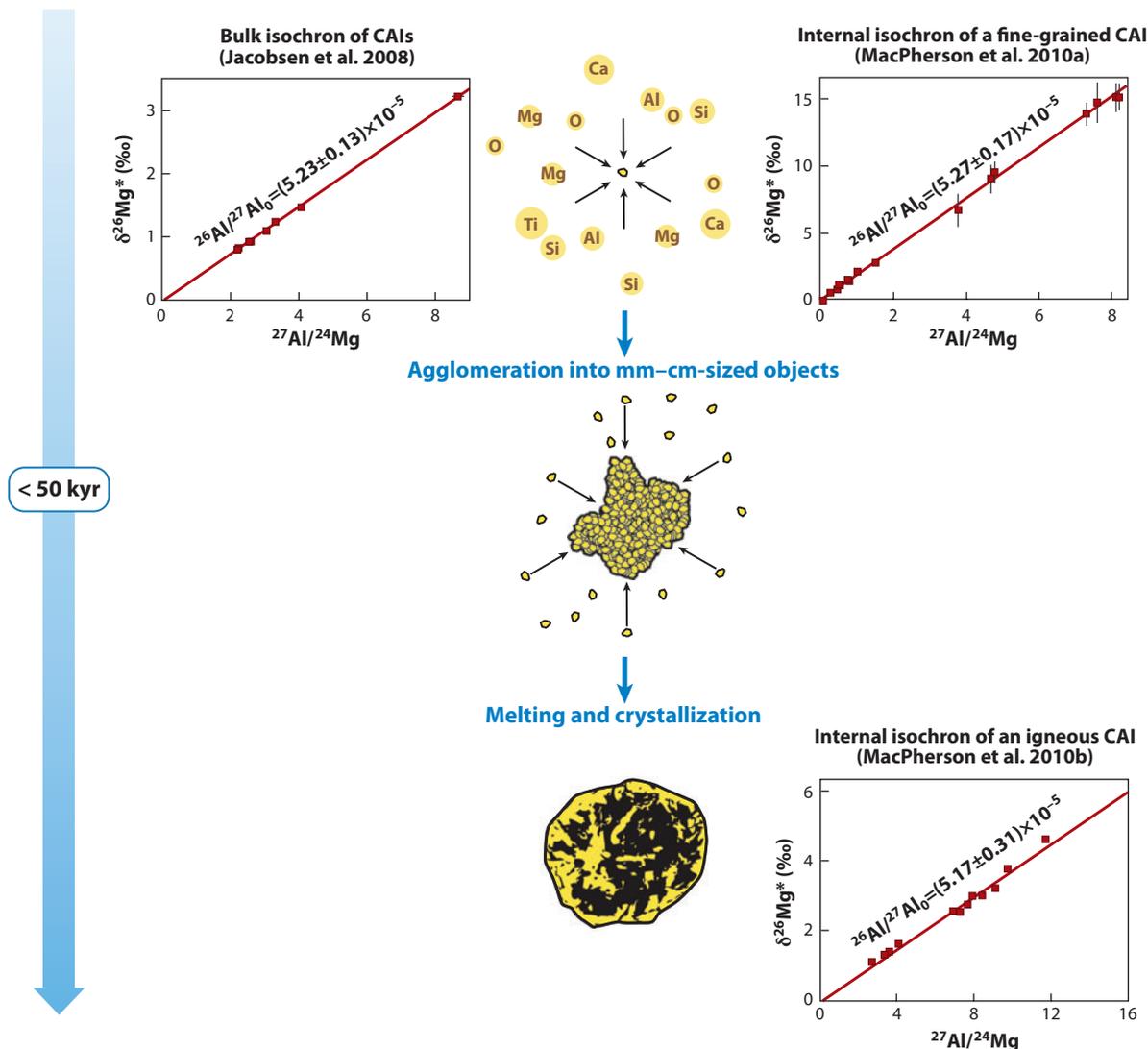
cometary material (Simon et al. 2008), indicating large-scale transport of dust in the protoplanetary disk (Ciesla 2007). The absolute age of refractory inclusions can be estimated using  $^{206}\text{Pb}$ - $^{207}\text{Pb}$  geochronology (Allègre et al. 1995, Amelin et al. 2002). In almost all studies,  $^{206}\text{Pb}$ - $^{207}\text{Pb}$  ages were calculated assuming a constant  $^{238}\text{U}/^{235}\text{U}$  ratio of 137.88, but recent work has shown that this value could vary from one CAI to another, possibly because of decay of short-lived radionuclide  $^{247}\text{Cm}$  ( $t_{1/2} = 15.6$  Myr) (Table 1) (see also Brennecka et al. 2010). Bouvier & Wadhwa (2010) did not measure directly the U isotopic composition in the CAI that they analyzed; instead, they estimated it on the basis of the observed chemical composition and obtained an age of  $4,568.2^{+0.2}_{-0.4}$  Myr. Amelin et al. (2010) reported a  $^{206}\text{Pb}$ - $^{207}\text{Pb}$  age of  $4,567.18 \pm 0.50$  Myr for a different CAI in which the  $^{238}\text{U}/^{235}\text{U}$  ratio was also measured. Therefore, there is no agreement at present on the best estimate of the age of the oldest solids formed in the solar system, although a 1-Myr time span in CAI U-Pb ages due to reheating episodes in the accretion disk cannot be excluded.

The  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics (Figure 2) in CAIs can be used to study the timing of dust condensation and agglomeration (Figure 4). Fractionation of the Al/Mg ratio in bulk CAIs was established during condensation, as Mg was more volatile than Al and was not totally condensed. Thus, the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio inferred from measurements of bulk CAIs (in CV chondrites, a class of CAI-rich carbonaceous chondrites that are named after the Vigarano meteorite) reflects the time when refractory dust condensed from gas in the inner part of the protoplanetary disk. Bulk CAI measurements define a single fossil isochron with a slope corresponding to an initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5.23 \pm 0.13 \times 10^{-5}$  (Jacobsen et al. 2008, Town 2008). A notable feature is that within uncertainties, all CAIs from CV chondrites define the same isochron, indicating that they all condensed within a time span of less than 20 kyr (Jacobsen et al. 2008, Thrane et al. 2006, Town 2008). MacPherson et al. (2010a) measured an internal  $^{26}\text{Al}$ - $^{26}\text{Mg}$  isochron in a fine-grained CAI (<10- $\mu\text{m}$  grain size) with a microstructure indicative of direct condensation from nebular gas. In that object, fractionation of the Al/Mg ratio between minerals must have occurred during condensation, and the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5.27 \pm 0.17 \times 10^{-5}$  must record that time. This is identical to the value defined by bulk CAI measurements, and it confirms the conclusion that condensation of refractory dust in the inner part of the disk occurred over a very short duration. This, together with the fact that they formed early, makes CAIs perfect time anchors for early solar system chronology.

Not all CAIs represent pristine nebular condensates. Many were melted after they were formed, possibly by nebular shock waves (Ciesla & Hood 2002, Desch & Connolly 2002, Hood & Horanyi 1993, Richter et al. 2006) or by passage near the Sun and launch to the meteorite-forming region by the X-wind (Shu et al. 1996). This melting episode gives us the opportunity to study the timescale of dust agglomeration. Indeed, the time of melting and subsequent crystallization represents a robust upper limit on the time of agglomeration. To estimate the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio at the time of crystallization of igneous (once molten) CAIs, one can calculate an internal isochron on the basis of measurements of individual minerals (Lee et al. 1976, 1977). MacPherson et al. (2010b) measured at high precision the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of four igneous CAIs and obtained values that range from  $4.24 \pm 0.36 \times 10^{-5}$  to  $5.17 \pm 0.31 \times 10^{-5}$ . The highest value corresponds to a time difference between condensation ( $^{26}\text{Al}/^{27}\text{Al}_0 = 5.23 \pm 0.13 \times 10^{-5}$ ; Jacobsen et al. 2008) and melting/crystallization ( $^{26}\text{Al}/^{27}\text{Al}_0 = 5.17 \pm 0.31 \times 10^{-5}$ ; MacPherson et al. 2010b) of less than 50 kyr. Some dust agglomerates could have formed later, but the study of CAIs shows that it took less than 50 kyr for condensates less than  $\sim 10$   $\mu\text{m}$  in size to agglomerate into centimeter-sized objects.

As CAIs represent ideal time anchors for early solar system chronology, one would like to put their formation into the broader context of solar system birth. In the inner part of the disk (within  $\sim 1$  AU), the temperature profile is almost isothermal. This is due to the thermostatic effect of

### Condensation of 1–10- $\mu\text{m}$ dust from nebular gas



**Figure 4**

Chronology of refractory dust condensation, agglomeration, and melting in the inner solar system. The principles behind the use of the  $^{26}\text{Al}$ – $^{26}\text{Mg}$  dating method in meteorites are presented in **Figure 2**. During cooling of the protosolar nebula, elements condensed into refractory dust <math>10\ \mu\text{m}</math> in size. This dust was then agglomerated into millimeter- to centimeter-sized objects. Some of these dust agglomerates subsequently became molten and crystallized and thus assumed a rounded shape. Isochrons calculated from measurements of bulk calcium-, aluminum-rich inclusions (CAIs) (Jacobsen et al. 2008) and individual minerals in a fine-grained CAI (MacPherson et al. 2010a) give initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios of  $\sim 5.2 \times 10^{-5}$ . This corresponds to the time when Al was fractionated from Mg owing to incomplete condensation of nebular gas into CAIs. An internal isochron calculated from measurements of individual minerals in an igneous (molten) CAI gives an identical initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $\sim 5.2 \times 10^{-5}$  (MacPherson et al. 2010b). This corresponds to the time when the centimeter-sized object was melted last and crystallized. The fact that the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios are identical within uncertainties for these two events (same slopes in  $\delta^{26}\text{Mg}^*$  versus  $^{27}\text{Al}/^{24}\text{Mg}$  diagrams) indicates that it took less than 50 kyr for micrometer-sized dust to agglomerate into centimeter-sized objects.

ferromagnesian silicate dust vaporization, which modulates the opacity (Boss 1998, Morfill 1988). Sufficiently high temperatures for the precursors of CAIs to condense could have been sustained in that region of the disk for several million years (Ciesla 2010, D'Alessio et al. 2005, Makalkin & Dorofeeva 2009). This duration is much longer than the time span of <20 kyr for condensation of the precursors of CAIs inferred from  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics (Jacobsen et al. 2008, MacPherson et al. 2010a, Thrane et al. 2006, Town 2008). Ciesla (2010) studied the dynamic fate of CAIs formed at different times in the disk and concluded that early-formed inclusions should dominate the inventory of CAIs found in primitive chondrites. The reasons are that (a) most inclusions are formed early, before the disk is drained of its mass and (b) early-formed inclusions are dispersed in the disk more easily by outward transport associated with angular momentum redistribution. Therefore, the time that refractory inclusions condensed marks the time when the protoplanetary disk reached its maximum size and when temperatures in the inner part first reached  $\sim 1,300$  to  $1,500$  K. This corresponds to the transition between class I and class II YSOs (examples of midplane temperature profiles in class I and II sources can be found in D'Alessio et al. 2005 and Whitney et al. 2003). This view is consistent with the observation that CAIs contain  $^{10}\text{Be}$ , which must have been produced by irradiation when the Sun was a T-Tauri star (see Section 3).

The timescale of grain coagulation in the inner part of the solar system estimated from the study of CAIs (<50 kyr to grow from <10  $\mu\text{m}$  to  $\sim 5$  mm) can be compared with model predictions and spectroscopic observations of grain-size distributions in YSOs. Dust grains in the interstellar medium have size distributions that peak at 0.2–0.3  $\mu\text{m}$ , with most grains having sizes of less than a micrometer (Mathis et al. 1977, Weingartner & Draine 2001). The theory of dust coagulation in protoplanetary disks predicts that those grains should grow rapidly (Dullemond & Dominik 2005, Weidenschilling 1980). For example, if one were to incorporate the physics of coagulation by Brownian motion, differential settlings to the midplane, and turbulent mixing, the expectation is that the grains should grow from <0.5  $\mu\text{m}$  to 1 cm on a timescale of 1,000 years (Dullemond & Dominik 2005). Models also predict a rapid depletion of the smallest grains, which is not seen in T-Tauri disks, indicating that small grains must be replenished constantly by fragmentation of larger dust agglomerates.

Astronomical observations of YSOs rely on two regions of the spectrum to examine grain growth in protoplanetary disks. The mid-infrared region (especially the Si-O stretching mode feature near 10  $\mu\text{m}$ ) can probe grain growth up to several micrometers at the surface of the disk within a few astronomical units of the central star (Bouwman et al. 2001, Kessler-Silacci et al. 2006, Przygodda et al. 2003). Infrared observations of pre-main sequence stars less than 1.5 Myr old show that dust particles grow rapidly to micrometer-sized agglomerates (Kessler-Silacci et al. 2006). The (sub)millimeter- to centimeter-wavelength region can probe grain growth up to centimeter-sized grains in the cold midplane of the outer disk (Calvet et al. 2002, Lommen et al. 2010, Ricci et al. 2010, Rodmann et al. 2006). Again, observations indicate rapid growth to millimeter- and centimeter-sized grains. Ricci et al. (2010) argued that this occurs before a YSO enters the class II evolutionary stage. Kwon et al. (2009) found evidence for grain growth in even younger, class 0, protostellar systems. Thus, astronomical observations are in good agreement with the conclusions based on dating of meteorite refractory inclusions and their constituents.

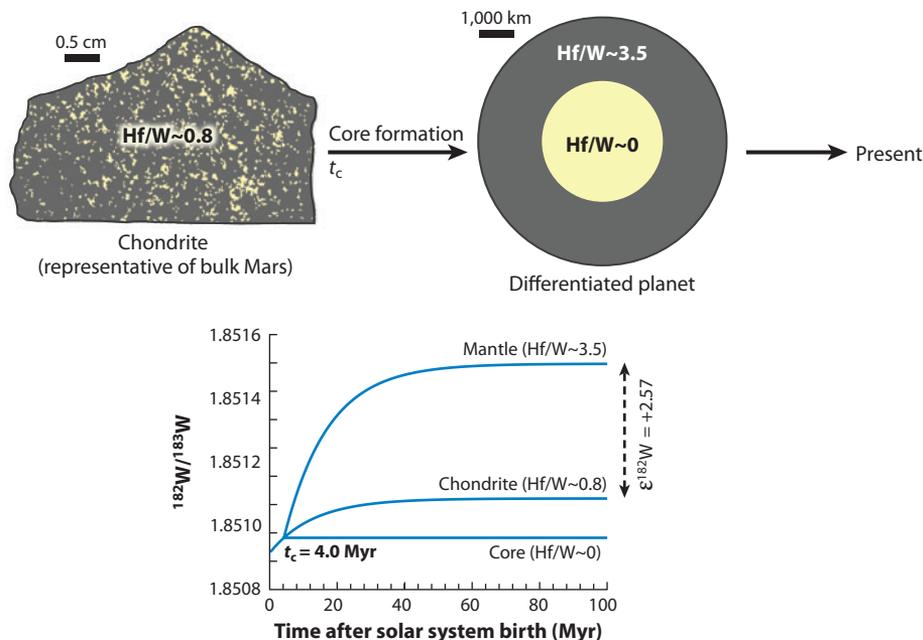
## 5. FROM DUST TO PLANETESIMALS

Planetesimals can be defined as objects formed in the accretion disk that were large enough (kilometer sized and up) to escape gas drag. A common view is that the production of planetesimals 1–10 km in size is the first step toward the formation of terrestrial planets (see Section 6). In this scenario, growth beyond  $\sim 1$  m in size, the so-called meter-size barrier, has always been difficult to

explain. Whereas models of dust-gas interactions predict that growth to meter-sized objects can proceed rapidly (i.e., in 100–1,000 years at 1 AU and  $6\text{--}7 \times 10^4$  years at 30 AU; Dullemond & Dominik 2005, Weidenschilling 1997) by collisions between smaller-sized aggregates (see Dominik et al. 2007 and references therein), further growth is problematic. Indeed, fragmentation and bouncing tend to prevail over growth in that size range (Zsom et al. 2010). This problem is exacerbated by the fact that meter-sized bodies are expected to have a short dynamic lifetime. Objects orbiting the Sun are bathed in nebular gas that rotates more slowly than the Keplerian velocity. As a consequence, they encounter gas drag, which causes an inward drift of the solids. This drift is minimum for small (0.1- $\mu\text{m}$ -sized) particles that are tightly coupled to the gas and for large (kilometer-sized) bodies that move in Keplerian orbits. The drift velocity is predicted to be maximum for meter-sized objects (up to  $\sim 10 \text{ m s}^{-1}$  radial drift for a nonturbulent nebula and objects of unit density orbiting the Sun between 1 and 30 AU; Cuzzi & Weidenschilling 2006). Thus, inward drift of particles in the meter-size range might occur so quickly as to outpace agglomeration. Turbulence can increase the residence time of the particles but might also counteract their settling onto the midplane (Dubrulle et al. 1994, Weidenschilling 1980).

Different paths to the formation of planetesimals have been proposed recently. All these models use turbulence to promote the formation of clumps of particles that can be dense enough to collapse into planetesimals by gravitational instability. They break the paradigm of a hierarchical growth because they predict direct formation of 100–1,000-km-sized planetesimals. A first class of models (Johansen et al. 2007) supposes that pressure maxima in a turbulent disk can concentrate meter-sized particles, leading to regions of high particle/gas ratios in which the gas is dragged to near-Keplerian speeds by the particles. These regions concentrate particles drifting from further out in the disk, in a process known as streaming instability, and gravitationally bound clumps develop. Calculations show that this process can produce large ( $\sim 1,000$ -km-sized) planetesimals in an extremely short time (a few to  $\sim 10$  orbital periods). A second class of models (Chambers 2010, Cuzzi et al. 2008) considers millimeter-sized particles (i.e., of chondrule size) that can be concentrated in low-vorticity regions of a turbulent disk. In some eddies, the particles reach a high enough concentration to form gravitationally bound clumps that can resist rotational breakup and the ram pressure of the surrounding gas. These clumps can ultimately undergo gradual contraction to form 10–100-km-sized planetesimals. This process, to be efficient, requires dust/gas ratios one to two orders of magnitude higher than the canonical solar ratio. Whereas the rate of formation of planetesimals can be rapid at 10 AU (a few tens of thousands of years), 100-km-sized planetesimals would require a few million years to form in regions inside the snow line (the heliocentric distance beyond which water ice is stable). Independent support for these scenarios comes from simulations of the growth of planetary embryos: these simulations can best reproduce the original size distribution of objects in the asteroid belt if the initial planetesimals have sizes in the range of 100–1,000 km (Morbidelli et al. 2009). All these models constitute a breakthrough in our understanding of the formation of planetesimals and make predictions concerning the size, the age, and the nature of planetesimals, all of which can be tested using meteorites. Abundances of short-lived radionuclides in meteorites demonstrate that primary accretion—by primary, we mean formed along the aforementioned principles of collapse of a gravitationally bound clump of particles—took place very early in the inner solar system, occurred quickly, and lasted at least  $\sim 4$  Myr after CAIs, until the nebula gas was dissipated. No data exist to date accretion of objects in the outer solar system.

The first constraint on the formation time of planetesimals is given by the  $^{182}\text{W}/^{183}\text{W}$  ratio of magmatic iron meteorites (see **Figure 5** for an explanation of  $^{182}\text{Hf}$ - $^{182}\text{W}$  systematics). After correction for cosmogenic effects resulting from exposure to galactic cosmic rays, the  $^{182}\text{W}/^{183}\text{W}$  ratios of magmatic iron meteorites are equally radiogenic or only slightly more radiogenic than the



**Figure 5**

Principles behind the use of  $^{182}\text{Hf}$ - $^{182}\text{W}$  systematics ( $t_{1/2} = 8.9$  Myr) for dating core-mantle segregation in the context of a simple two-stage model of core formation. In a first stage ( $t < t_c$ , where  $t_c$  stands for time of core formation), the planetary body is assumed to follow a chondritic evolution. In chondrites, metal (yellow) is intimately mixed with silicate (gray) at the subcentimeter scale. In a second stage ( $t = t_c$ ), the metal melts and is segregated from the silicate mantle to form a core. Given that Hf is lithophile whereas W is moderately siderophile, the Hf/W ratio of the mantle is higher than that of the core or chondrites. After core formation,  $^{182}\text{Hf}$  continues to decay into  $^{182}\text{W}$ , resulting in a more radiogenic (higher)  $^{182}\text{W}/^{183}\text{W}$  ratio in the mantle compared with that of the chondrites. The Hf/W ratio of the core is  $\sim 0$ , so its W isotopic composition is identical to the chondritic composition at  $t_c$ . Measuring the  $^{182}\text{W}/^{183}\text{W}$  ratio of planetary mantles ( $\epsilon^{182}\text{W}_{\text{mantle}}$  in the following equation) and knowing their Hf/W ratios ( $f_{\text{mantle}}^{\text{Hf/W}}$ ), one can determine the time that the composition of the mantle departed from the chondritic evolution, which corresponds to the time of core formation ( $t_c$ ),  $\epsilon^{182}\text{W}_{\text{mantle}} = q_W f_{\text{mantle}}^{\text{Hf/W}} ({}^{182}\text{Hf}/{}^{180}\text{Hf})_0 e^{-\lambda t_c}$ , where  $\epsilon^{182}\text{W}_{\text{mantle}} = [({}^{182}\text{W}/{}^{183}\text{W})_{\text{mantle}} / ({}^{182}\text{W}/{}^{183}\text{W})_{\text{CHUR}} - 1] \times 10^4$ ,  $q_W = 10^4 \times ({}^{180}\text{Hf}/{}^{182}\text{W})_{\text{CHUR}}$ , and  $f_{\text{mantle}}^{\text{Hf/W}} = (\text{Hf/W})_{\text{mantle}} / (\text{Hf/W})_{\text{CHUR}} - 1$ . The values for the chondritic uniform reservoir (CHUR) represent the bulk composition of Mars (Lodders & Fegley 1997). We have  $\epsilon^{182}\text{W}_{\text{mantle}} = +2.57$  (Foley et al. 2005, Kleine et al. 2007),  $q_W = 1.07 \times 10^4$  (Kleine et al. 2007), and  $f_{\text{mantle}}^{\text{Hf/W}} = 3.38$  (Dauphas & Pourmand 2011). The initial  $({}^{182}\text{Hf}/{}^{180}\text{Hf})_0$  ratio of  $9.72 \pm 0.44 \times 10^{-5}$  is well established from measurements of refractory inclusions (Burkhardt et al. 2008), and the decay constant  $\lambda_{182\text{Hf}}$  is  $0.078 \text{ Myr}^{-1}$  (Vockenhuber et al. 2004). Applying this simple model to the martian mantle would give a time of core formation of  $\sim 4.0$  Myr. However, this model may be inappropriate if core formation in embryos and planets was a protracted phenomenon that tracked the accretion history.

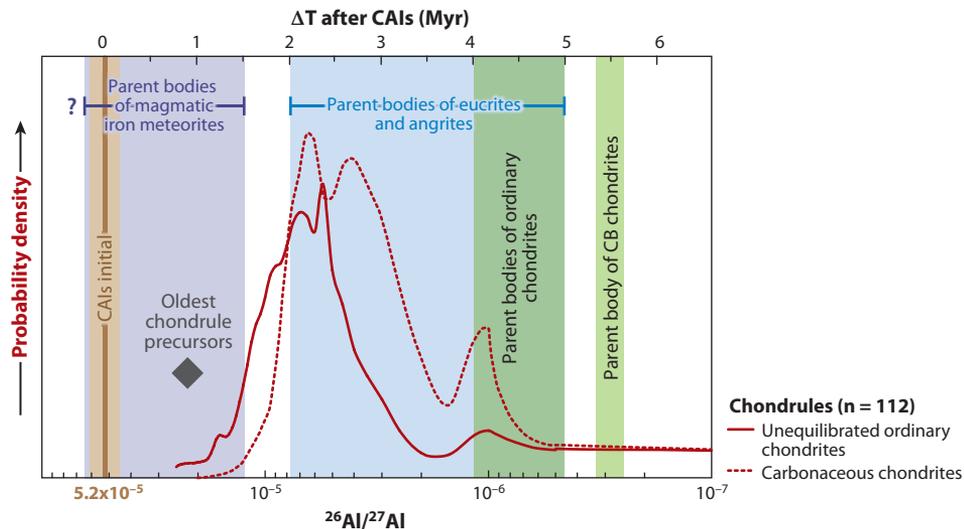
solar system initial ratio defined by CAIs (Burkhardt et al. 2008; Kleine et al. 2005, 2009; Markowski et al. 2006, Qin et al. 2008). This implies that the parent bodies of magmatic iron meteorites (bodies of  $\sim 10$ – $200$  km in size; Chabot & Haack 2006) accreted  $\sim 0$ – $1.5$  Myr after the formation of CAIs (although analytical errors permit accretion to begin a few hundred thousand years earlier than the formation of CAIs). Any body exceeding  $\sim 1$  km formed within one million years of the formation of CAIs would likely undergo rapid metal-silicate differentiation in response to the heat released by the decay of  $^{26}\text{Al}$ . For instance, a 5-km-diameter planetesimal (with  ${}^{26}\text{Al}/{}^{27}\text{Al} = 5 \times 10^{-5}$

and initial temperature  $T$  at 100 K) would reach 1,500 K in its core within  $\sim 4 \times 10^5$  years, whereas its surface would remain at  $T < 400$  K (e.g., Ghosh et al. 2006, Hevey & Sanders 2006, LaTourette & Wasserburg 1998). Basaltic angrites, which, according to their  $^{26}\text{Al}$ ,  $^{182}\text{Hf}$ , and Pb-Pb systematics (Amelin 2008, Baker et al. 2005, Markowski et al. 2007, Schiller et al. 2010, Spivak-Birndorf et al. 2009), are the oldest non-iron-differentiated meteorites (crystallization ages of  $\sim 5$  Myr after CAI formation) and are likely fragments of planetesimal crusts formed within  $\sim 2$ – $3$  Myr of CAI formation. Such a rapid accretion of bodies  $\sim 10$ – $100$  km in size shows that the mechanisms described by Johansen et al. (2007) and Cuzzi et al. (2008) could have operated in the accretion disk. Early formation of large planetary objects might have induced collisional evolution and scattering of the rest of the population of planetesimals (Bottke et al. 2006).

The second constraint on the formation time of planetesimals comes from chondrules, which show that chondrite parent bodies accreted over a longer time period of 3–4 Myr, as predicted in the dynamic models of Cuzzi et al. (2008) and Chambers (2010). Pb-Pb ages, short-lived  $^{26}\text{Al}$ , and  $^{53}\text{Mn}$  indicate that chondrules crystallized  $\sim 1$ – $3$  Myr after the formation of CAIs (e.g., Kita et al. 2005a and references therein). High-precision  $^{26}\text{Al}$  isochrons (see **Figure 3c**) in type II chondrules from Semarkona show that they have crystallization ages from 1.2 to 4 Myr (Villeneuve et al. 2009). All the existing internal  $^{26}\text{Al}$  isochrons in chondrules taken at face value (**Figure 6**), whatever their precisions are, show that chondrites did not form until  $\sim 4$  Myr after CAI formation. Detailed geochronological studies of some chondrites (H-type chondrites) have shown that they probably came from a parent body that was  $\sim 100$  km in diameter (e.g., Trieloff et al. 2003, Bouvier et al. 2007). The samples that come from near the center of that parent body have the same chemical compositions and same constituents as those that come from more external regions. As discussed by Cuzzi et al. (2008), this is consistent with the idea that such planetesimals were formed by collapse of a high-density (Cuzzi & Alexander 2006) clump of gravitationally bound chondrules, refractory inclusions, and fine dust. Chondrites do not look like rubble piles of unrelated meter-sized boulders. Thus, primary planetesimals could have formed throughout the accretion history of the disk.

Secondary planetesimals can be defined as those formed following collisions between primary planetesimals. Different hints for very early and late collisions and fragmentation of planetesimals exist. The first hint comes from Mg-rich olivines in a peculiar type of chondrule (the so-called type I chondrule). These olivines are present in chondrules as relict clasts. They have a granoblastic texture (a rock texture in which equant crystals meet at  $120^\circ$  triple junctions) analogous to that of terrestrial mantle rocks (Libourel & Krot 2007). This suggests that they could be fragments of the mantles of disrupted planetesimals that accreted very early, akin to the parent bodies of magmatic iron meteorites or angrites. Oxygen isotope systematics supports an origin from several planetesimals characterized by different oxygen isotopic compositions (Libourel & Chaussidon 2011). The unradiogenic Mg isotopic composition of several of these olivines is consistent with an early formation, within  $\sim 0.1$ – $1$  Myr of CAI formation (Villeneuve et al. 2011). The second hint comes from CB chondrites, a class of metal-rich carbonaceous chondrites that are named after the Bencubbin meteorite. The CB chondrites contain chondrules that have young Pb-Pb ages ( $\sim 5.5$  Myr after CAIs from CV chondrites; Krot et al. 2005a) and CAIs that show mass fractionation of Mg isotopes along with a low abundance of  $^{26}\text{Al}$  ( $^{26}\text{Al}/^{27}\text{Al} < 4.6 \times 10^{-6}$ ; Gounelle et al. 2007). This is in agreement with formation in a plume generated by an impact between planetesimals or early-formed embryos.

All these observations are in agreement with the latest dynamic models and indicate that planetesimals can form over different timescales (the ones formed early and rapidly were molten and differentiated, whereas those formed later from millimeter-sized dust remained undifferentiated). The view that the evolution of the nebula occurred in discrete chronological eras (i.e.,



**Figure 6**

Constraints from short-lived radionuclides on the timing of primary accretion. Relative ages are derived from  $^{182}\text{Hf}$  for magmatic iron meteorites (Burkhardt et al. 2008; Kleine et al. 2005, 2009; Markowski et al. 2006, 2007; Qin et al. 2008),  $^{26}\text{Al}$  for chondrules [total of 112 chondrules, including 68 for unequilibrated ordinary chondrites (*solid curve*) and 44 from carbonaceous chondrites (*dashed curve*); data from Hsu et al. 2003; Hutcheon & Hutchison 1989; Hutcheon et al. 2000; Kita et al. 2000, 2005b; Kunihiro et al. 2004; Kurahashi et al. 2008; Mostéfaoui et al. 2000; Nagashima et al. 2007, 2008; Rudraswami & Goswami 2007; Rudraswami et al. 2008; Russell et al. 1996; Sugiura & Krot 2007; Villeneuve et al. 2009; Yurimoto & Wasson 2002], and  $^{26}\text{Al}$  for eucrites (originating most probably from the asteroid Vesta) and angrites (Baker et al. 2005, Bizzarro et al. 2005, Schiller et al. 2010, Spivak-Birndorf et al. 2009). The boxes shown for magmatic irons and for angrites and eucrites correspond to the duration from accretion to global melting ( $^{26}\text{Al}$  and  $^{182}\text{Hf}$  give access to differentiation ages for these bodies, and the accretion age is back-calculated from modeling of heating by  $^{26}\text{Al}$ ; e.g., Qin et al. 2008). Contrary to the classical view of planetary formation, it is clear that accretion started very early with some parent bodies of magmatic iron meteorites that could be as old as calcium-, aluminum-rich inclusions (CAIs), and that it continued most probably for up to 4 Myr. The age distribution of chondrules could be interpreted either as the reflection of some major episodes of formation between  $\sim 1$  and 4 Myr after CAI formation or as the result of a biased sampling (or preservation) of the population existing in the disk at the time of chondrite formation. Whatever the exact origin of chondrules' age distribution, this demonstrates the existence of processes able to preserve chondrules from accreting to the Sun for several million years. Chondrites were formed late (most likely  $\sim 4$  Myr after CAI). Secondary planetesimals can be made at any time from collisions between primary planetesimals. CB chondrites (a class of metal-rich carbonaceous chondrites that are named after the Bencubbin meteorite; see Section 5) are probably an example of such an episode that happened late,  $\sim 5.5$  Myr after CAI formation (Krot et al. 2005a). Probability density for chondrules is shown in linear scale.

agglomeration of micrometer-sized condensates, formation of meter-sized objects, and formation of kilometer-sized planetesimals) appears incorrect, as planetesimal formation spanned several millions of years and overlapped with embryo formation.

## 6. FROM PLANETESIMALS TO MARS, A POSSIBLE PLANETARY EMBRYO

In the classical model of planetary formation, the growth of planetesimals (from  $\sim 1$  to possibly 1,000 km in diameter) into planetary embryos (1,000–5,000 km) proceeds in two stages. As

planetesimals collide with one another, the largest bodies can exert a stronger gravitational focus on the surrounding objects, and their growth can outpace that of the smaller planetesimals ( $dM/dt \propto M^{4/3}$ ) in a process known as runaway growth (Greenberg et al. 1978, Wetherill & Stewart 1993). However, as they grow in size, the embryos dynamically excite the swarm of planetesimals around them. Planetary bodies involved in close encounters are less likely to collide when the relative velocities increase, so the largest bodies continue to grow, but they grow at a slower pace in a process known as oligarchic growth (Ida & Makino 1993, Kokubo & Ida 1998). As discussed in Section 5, this simple picture has been questioned by two recent studies that proposed new models for the formation of planetesimals [see the review by Chiang & Youdin (2010)]. Johansen et al. (2007) showed that in turbulent circumstellar disks, dust could concentrate in high-pressure regions (Haghighipour & Boss 2003) for periods of time long enough to allow gravitationally bound clumps of meter-sized objects to collapse into planetesimals. Cuzzi et al. (2008) and Chambers (2010) showed that millimeter-sized particles such as chondrules could concentrate in the cascade of eddies associated with turbulence in the disk. Again, simulations showed that such clumps could survive for a period of time long enough to allow particles to sediment into planetesimals. A common feature of both models is that the planetesimals may have started larger (i.e.,  $\sim 100$ – $1,000$  km; Chambers 2010, Cuzzi et al. 2008, Johansen et al. 2007) than previously thought (i.e.,  $\sim 1$  km; Goldreich & Ward 1973), thus largely bypassing the stage of runaway growth. These results have important implications for the mode and timescale of embryo formation. Using a model that started with large planetesimals (100–1,000 km) created over a 2-Myr interval, Morbidelli et al. (2009) showed that the formation of embryos could take place on a timescale of a few million years (i.e., within  $\sim 3$  Myr).

Establishing the chronology of embryo formation using extinct radionuclides is not straightforward because most of this material was incorporated into the terrestrial planets during their accretion. However, dynamic simulations of terrestrial planet formation have difficulties explaining the small mass of Mars compared with the masses of Earth and Venus (Chambers & Cassen 2002, Raymond et al. 2009, Wetherill 1991). One possibility is that Mars is actually a planetary embryo that escaped ejection and collision with other embryos (Chambers 2004, Chambers & Wetherill 1998). If that is correct, its accretion timescale should give us some clues about the formation time of embryos in the inner part of the solar system. The best tool to investigate this question is the radionuclide  $^{182}\text{Hf}$ , which decays to  $^{182}\text{W}$  with a  $t_{1/2}$  of 8.9 Myr (**Figure 5**; see also Dauphas & Pourmand 2011; Foley et al. 2005; Jacobsen 2005; Kleine et al. 2007, 2009; Lee & Halliday 1997; Nimmo & Kleine 2007). Hf is a lithophile (silicate rock-loving) element, meaning that when planetary objects melted and metallic cores formed, it was retained in the silicate mantles. Conversely, W is a moderately siderophile (metal-loving) element, meaning that it was largely scavenged into planetary cores during differentiation. As a result of these contrasting behaviors, the mantles of differentiated objects have high Hf/W ratios relative to bulk planets represented by chondrites, whereas their cores have Hf/W  $\sim 0$ . If planetary bodies differentiated early, while  $^{182}\text{Hf}$  was still alive (within  $\sim 50$  Myr of the formation of the solar system), their mantles should show excess radiogenic  $^{182}\text{W}$  relative to that in chondrites owing to the decay of  $^{182}\text{Hf}$ . In contrast, if core-mantle segregation occurred after  $^{182}\text{Hf}$  had decayed, the mantles should have  $^{182}\text{W}$  isotopic abundance identical to that in chondrites. Thus, by measuring the  $^{182}\text{W}/^{183}\text{W}$  and Hf/W ratios of the martian mantle, one can estimate a model age of core formation, which is related to the timescale of accretion. Because the W isotopic variations are tiny, one uses the  $\epsilon$  notation to report them:

$$\epsilon^{182}\text{W}_{\text{mantle}} = \left[ \left( \frac{^{182}\text{W}}{^{183}\text{W}} \right)_{\text{mantle}} / \left( \frac{^{182}\text{W}}{^{183}\text{W}} \right)_{\text{CHUR}} - 1 \right] \times 10^4.$$

CHUR represents the composition of chondrites, which are the assumed building blocks of Mars. Measurements of the Shergottite-Nakhlite-Chassignite group of meteorites, which are thought to come from Mars (Bogard & Johnson 1983 and references therein), give the W isotopic composition of the martian mantle relative to chondrites as  $\epsilon^{182}\text{W} = +2.57$  (Foley et al. 2005, Kleine et al. 2007). The other important ingredient for applying the  $^{182}\text{Hf}$ - $^{182}\text{W}$  system to Mars is the Hf/W ratio of its mantle, which can be expressed using a fractionation factor,

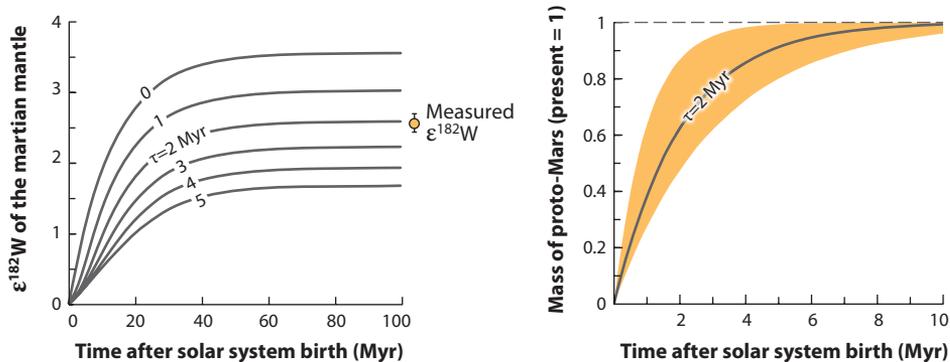
$$f_{\text{mantle}}^{\text{Hf/W}} = (\text{Hf/W})_{\text{mantle}} / (\text{Hf/W})_{\text{CHUR}} - 1.$$

Again, CHUR represents chondritic composition, assumed to represent the composition of bulk Mars. Nimmo & Kleine (2007) concluded that the calculated age of core formation was uncertain owing to a large uncertainty in the value of  $f_{\text{mantle}}^{\text{Hf/W}}$ . However, Dauphas & Pourmand (2011) have redetermined this parameter using a new method, and they have obtained a precise value of  $f_{\text{mantle}}^{\text{Hf/W}} = 3.38$ , which provides new insights into the accretion history of Mars.

There is considerable uncertainty about the mode of core formation in embryos and planets (Ricard et al. 2009, Rubie et al. 2003). The simplest scenario is that core formation occurred instantaneously after the embryo or planet completed its accretion (**Figure 5**). For Mars, this gives a time of core formation of 4.0 Myr after the birth of the solar system (see equation 14 of Jacobsen 2005), but this model may not be realistic. Instead, core formation may have been a protracted phenomenon that tracked the accretion of the planet. This alternative model assumes that each time a planetesimal is accreted, its metal and silicate portions are fully equilibrated with the mantle of the growing embryo. Thus, the increment of metal that is subsequently removed to the core has the same W isotopic composition as that of the martian mantle at that time (Halliday et al. 1996, Jacobsen 2005, Jacobsen & Harper 1996). In this scenario, the core grows in constant proportion with the mass of Mars and therefore tracks the accretion of the planet. The assumption of complete equilibration between accreted planetesimals and the mantle of the growing embryo (Mars) is reasonable given the difference in scale between the impactor and the target and the fact that the target may have been molten (Nimmo & Agnor 2006). The accretion history is parameterized using the following equation (Jacobsen & Harper 1996, Wetherill 1986),

$$M = M_{\text{final}} (1 - e^{-t/\tau}),$$

where  $M_{\text{final}}$  is the present mass of Mars and  $\tau$  is the accretion timescale. Given  $\tau$  and knowing  $f_{\text{mantle}}^{\text{Hf/W}}$ , calculating  $\epsilon^{182}\text{W}_{\text{mantle}}$  is possible (**Figure 7**). If the accretion timescale was significantly shorter than 2 Myr, one would expect the martian mantle to have more radiogenic  $^{182}\text{W}$  (higher  $\epsilon^{182}\text{W}$ ) than is measured. Conversely, if the accretion timescale of Mars was much longer than  $\sim 2$  Myr, one would expect it to have less radiogenic  $^{182}\text{W}$  (lower  $\epsilon^{182}\text{W}$ ) than is measured. The growth curve is therefore constrained to  $\tau \sim 2$  Myr (**Figure 7**) (see also Dauphas & Pourmand 2011). Such a short timescale is consistent with the idea that Mars is a stranded planetary embryo and with results of dynamic simulations that indicate formation of planetary embryos within the first few million years of the birth of the solar system (Chambers 2004, Morbidelli et al. 2009). The chronology of planetesimal formation and embryo formation inferred from meteorites (see Sections 5 and 6) indicates that the two processes largely overlapped. Some primary planetesimals such as the parent bodies of H-type chondrites (100 km) were formed a few million years after the formation of CAIs, when Mars ( $\sim 6,800$  km) had already reached a significant size. Embryo formation took place when gas was still present. This is consistent with the core accretion model of giant planet formation that requires accretion of gas onto rocky cores that are formed before dissipation of the nebula (e.g., Mizuno 1980, Pollack et al. 1996).

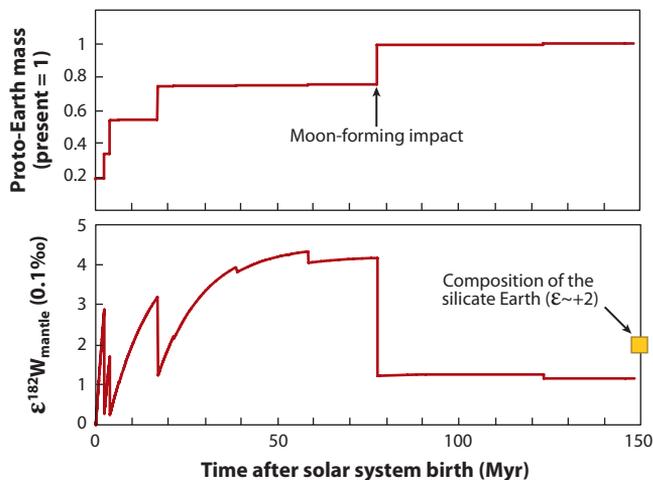


**Figure 7**

Accretion history of Mars as derived from  $^{182}\text{Hf}$ - $^{182}\text{W}$  systematics of martian meteorites. The growth of Mars is assumed to follow the parameterization  $M = M_{\text{final}}(1 - e^{-t/\tau})$ , where  $\tau$  is the accretion timescale (corresponding to the time after the onset of accretion when the planet reached approximately two-thirds of its present size). Given that parameterization, it is possible to estimate the shift in the isotopic abundance of  $^{182}\text{W}$  in the martian mantle for different values of  $\tau$  (equation 65 of Jacobsen 2005),  $\epsilon^{182}\text{W}_{\text{mantle}} = q_{\text{W}}(^{182}\text{Hf}/^{180}\text{Hf})_0 f_{\text{mantle}}^{\text{Hf}/\text{W}} \lambda_{^{182}\text{Hf}} \int_0^t [(1 - e^{-\xi/\tau})/(1 - e^{-t/\tau})]^{1 + f_{\text{mantle}}^{\text{Hf}/\text{W}}} e^{-\lambda\xi} d\xi$ . The notations and their numerical values for Mars are given in the caption of **Figure 5**. The left panel shows that the measured  $^{182}\text{W}$  excess in the martian mantle can be explained only by an accretion timescale of  $\tau \sim 2$  Myr, which corresponds to the accretion history shown in the right panel (Dauphas & Pourmand 2011).

## 7. FROM EMBRYOS TO EARTH, A TERRESTRIAL PLANET

The outcome of oligarchic growth is the formation of numerous Moon- to Mars-sized embryos surrounded by a swarm of planetesimals (see Section 6). Kokubo & Ida (2000) showed that embryos form at regular orbital distances and that the mass of each embryo depends on the size of its feeding zone and on the surface density of the disk at that location. Terrestrial planets grew by collisions between these planetary embryos; this process is known as chaotic growth because it is entirely stochastic. The transition from oligarchic growth to chaotic growth occurred when the mass locked up in embryos was comparable to that in planetesimals (Kenyon & Bromley 2006). This stage can be followed numerically by simulations in which the trajectories of all embryos are computed (i.e., N-body simulations; Chambers 2001, Chambers & Wetherill 1998, Cox & Lewis 1980, Wetherill 1980). The models are initialized by placing embryos at regular heliocentric distances with masses of individual embryos that depend on the assumed density of the disk with distance and then following the collision merging of these embryos subjected to the laws of gravitation (e.g., figure 1 of Chambers & Wetherill 1998). By convention, in simulations, the larger of two bodies involved in a collision leading to an Earth-like planet is termed the proto-Earth. Early models that tracked only embryos, without planetesimals, found that the planets formed were on orbits that were too eccentric and inclined compared with the real ones. The most likely solution to this problem is that planetesimals were also present when accretion of the terrestrial planets started (Section 6; see also Kenyon & Bromley 2006). In simulations, this reduces the eccentricities of the embryos by dynamic friction and produces terrestrial planets that are more akin to the real ones (Chambers 2001, O'Brien et al. 2006). The presence of the gas giants Jupiter and Saturn—which must have formed within a few million years of the formation of the solar system, before dissipation of nebular gas—also has a strong influence on the outcome of the simulations (Levison & Agnor 2003). State-of-the-art accretion models for Earth predict that the accretion should extend over several tens of million years (**Figure 8**).



**Figure 8**

Predicted  $\epsilon^{182}\text{W}$  evolution of the silicate mantle of the proto-Earth (*bottom*) for an N-body simulation of Earth's accretion (*top*) (Kleine et al. 2009, Raymond et al. 2006). This model reproduces approximately the  $\epsilon^{182}\text{W}$  value of the silicate Earth ( $\sim +2$ ; Dauphas et al. 2002a, Kleine et al. 2002, Schoenberg et al. 2002, Yin et al. 2002). Here, it is assumed that each time an embryo is accreted by the proto-Earth, it is equilibrated with its mantle before metal segregation. A better match between the modeled and measured W isotopic compositions would be obtained by allowing for incomplete equilibration (Allègre et al. 2008, Halliday 2004, Kleine et al. 2009, Nimmo et al. 2010). This model is consistent with the constraint that the Moon-forming impact must have occurred 30–150 Myr after solar system birth (Bourdon et al. 2008, Touboul et al. 2007, Yin et al. 2010, König et al. 2011). Because the model considers complete equilibration during impact, the  $\epsilon^{182}\text{W}$  is partially reset to chondritic composition ( $\epsilon^{182}\text{W} = 0$ ) at each collision with an embryo, which explains the sawtooth pattern in  $\epsilon^{182}\text{W}$ .

As discussed in the case of Mars (see Section 6), the accretion timescale of Earth can be inferred by applying the principles of  $^{182}\text{Hf}$ - $^{182}\text{W}$  systematics (for details, see the recent reviews by Jacobsen 2005 and Kleine et al. 2009). Lee & Halliday (1995) were the first to promote the use of  $^{182}\text{Hf}$ - $^{182}\text{W}$  systematics to constrain the time of core formation on Earth. They had concluded that the silicate Earth had a  $^{182}\text{W}/^{183}\text{W}$  ratio identical to that of chondrites, implying that the core had formed late, after complete decay of  $^{182}\text{Hf}$ . However, these measurements were later shown to be erroneous (Kleine et al. 2002, Schoenberg et al. 2002, Yin et al. 2002). In 2002, Dauphas et al. (2002a) reinterpreted some earlier W isotope data of enstatite chondrites (Lee & Halliday 2000) and concluded that Earth's mantle had excess radiogenic  $^{182}\text{W}$  corresponding to  $\epsilon^{182}\text{W}_{\text{mantle}} = +2.13 \pm 0.53$ . That same year, Yin et al. (2002), Kleine et al. (2002), and Schoenberg et al. (2002) remeasured some of the carbonaceous chondrites measured earlier by Lee & Halliday (1995) and concluded, too, that  $\epsilon^{182}\text{W}_{\text{mantle}} \approx +2$ . The presence of excess  $^{182}\text{W}$  in the terrestrial mantle relative to what is found in chondrites implies that the core formed early, while  $^{182}\text{Hf}$  was still alive.

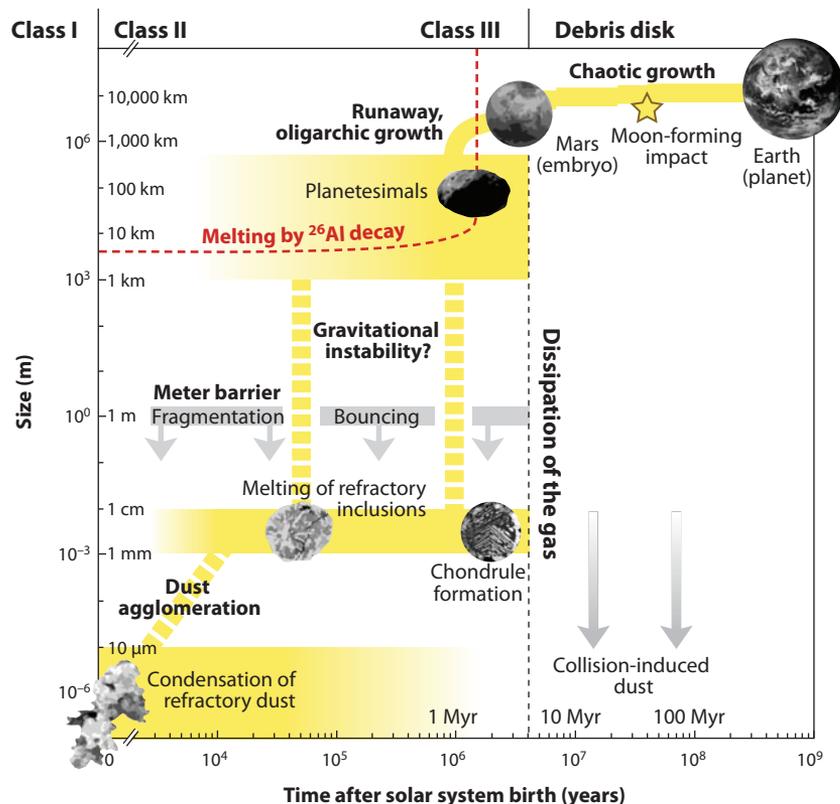
To quantify how early Earth's core formed, one must rely on models of accretion and core differentiation. As discussed in Section 6, the simplest model is to assume that core formation occurred instantaneously at some time after the birth of the solar system (**Figure 5**). The numerical values to use for Earth's mantle (e.g., assuming enstatite-chondrite-like composition for the bulk Earth) are  $\epsilon^{182}\text{W}_{\text{mantle}} = +2.1$  (Dauphas et al. 2002a),  $q_{\text{W}} = 1.25 \times 10^4$  (Lee & Halliday 2000), and  $f_{\text{mantle}}^{\text{Hf/W}} = 21$  (Arevalo & McDonough 2008, Dauphas & Pourmand 2011, Newsom et al. 1996). The calculated instantaneous time of core formation on Earth is  $\sim 32$  Myr (Dauphas et al. 2002a,

Kleine et al. 2002, Schoenberg et al. 2002, Yin et al. 2002). One can also calculate the accretion timescale of Earth for an exponentially decaying rate of accretion (see Section 6), and the result is  $\tau \sim 10$  Myr (Jacobsen 2005, Kleine et al. 2009, Yin et al. 2002), which represents the time that Earth would have reached two-thirds of its present size. These results indicate that accretion of Earth took much longer than that of Mars, which is consistent with the idea that their modes of formation differed. However, these two models are overly simplistic, as accretion of Earth corresponded neither to a single differentiation event nor to continuous accretion of small bodies.

For Earth, one can directly use the output of N-body simulations to predict  $\epsilon^{182}\text{W}$  in the mantle (Jacobsen 2005, Nimmo & Agnor 2006, Nimmo et al. 2010), which can then be compared with the measured value of  $\sim +2$ . Among the simulations that make Earth-like planets, those that produce the appropriate amount of radiogenic excess  $^{182}\text{W}$  are retained as likely. In the case of Earth, an important difficulty is that growth involved impacts between large bodies, and it is unclear whether the impactor equilibrated with the mantle completely before segregation of metal into the core (Halliday 2004). In an extreme scenario, the cores of impacting embryos involved in collisions would merge without equilibrating at all with the mantle. If this were true, the W isotopic composition of Earth's mantle would give the age of core formation on embryos or planetesimals rather than the age of core formation on Earth. This is not the case (see Sections 5 and 6), so one can rule out this extreme model. Some models assume that only a fraction of the impactor is equilibrated with the mantle of the proto-Earth (Allègre et al. 2008, Dahl & Stevenson 2010, Halliday 2004, Kleine et al. 2009, Nimmo et al. 2010). As shown by Halliday (2004) and Allègre et al. (2008), doing so can help reconcile the age of core formation inferred from  $^{182}\text{Hf}$ - $^{182}\text{W}$  with the age of core formation inferred from Pb isotopes (Allègre et al. 1982, 1995; Galer & Goldstein 1996) and the age of Earth's atmosphere obtained using  $^{129}\text{I}$ - $^{129}\text{Xe}$  systematics (Wetherill 1975, Zhang 1998).

An important constraint on the accretion of Earth arises from estimates of the age of the Moon. The current paradigm of Moon formation is that it was produced by a giant impact between a Mars-sized embryo (Theia) and the proto-Earth (Canup & Asphaug 2001). This event occurred at the end of the accretion of Earth, corresponding to an increment of  $\sim 10\%$  of its present mass. The lunar mantle has a Hf/W ratio that is higher than that of Earth's mantle (see Touboul et al. 2007, but see also Yin et al. 2010, König et al. 2011). Thus, if the Moon formed while  $^{182}\text{Hf}$  was still alive, the lunar rocks should show excess  $^{182}\text{W}$  compared with that of Earth's mantle. Instead, Touboul et al. (2007) found that the W isotopic composition of the lunar mantle was indistinguishable from that of Earth. This finding has two important implications: (a) the Moon was equilibrated isotopically with the proto-Earth mantle during impact (e.g., Pahlevan & Stevenson 2007), and (b) the Moon formed late, after  $^{182}\text{Hf}$  had decayed. Combining this result with other chronological information on the crystallization of the lunar magma ocean (Carlson & Lugmair 1988, Norman et al. 2003), Touboul et al. (2007) and Bourdon et al. (2008) suggested that the Moon formed 50–150 Myr after the birth of the solar system, implying that Earth continued to grow by collisions with embryos for more than 50 Myr. Some numerical simulations give a protracted accretion history of Earth and are consistent with the record of extinct radionuclides in the Earth-Moon system (**Figure 8**) (Kleine et al. 2009). However, our knowledge of the lunar and terrestrial mantle Hf/W ratios are likely less precise than those assumed by Touboul et al. (2007). If, for example, the Hf/W ratio is identical to that of Earth, it would restrict lunar formation to  $\sim 30$ – $40$  Myr after CAI formation (Yin et al. 2010, König et al. 2011), which would be consistent with  $^{176}\text{Lu}/^{176}\text{Hf}$  evidence from ancient terrestrial zircons (Harrison 2009).

In circumstellar disks of YSOs, the formation of giant planets may be detectable by the development of annular gaps (e.g., Calvet et al. 2002). Some giant planets have been detected directly in debris disks, some as young as 10 Myr old (e.g., Lagrange et al. 2010). Terrestrial planet formation



**Figure 9**

Extinct radionuclide perspective on the formation of the solar system. For cosmochemists, time zero is marked by the condensation of refractory dust in the inner part of the disk, which corresponds to the transition between class I and II stellar sources. Less than 50 kyr after condensation, dust agglomerated into millimeter- and centimeter-sized objects. Objects of that size (refractory inclusions and chondrules) were present in the disk for  $\sim 4$  Myr. Fragmentation and bouncing prevented growth by agglomeration beyond the meter-size barrier. Instead, gravitational instability of large clumps of chondrules and refractory inclusions led to the formation of planetesimals up to several hundreds of kilometers in size. Planetesimal formation spanned several million years. Runaway and oligarchic growth produced Mars-sized embryos on a timescale of a few million years. No primary planetesimal was formed after  $\sim 4$  Myr after solar system birth, which may correspond to the dissipation of the gas and the transition between a class III stellar source and the debris disk. Earth formed by chaotic growth over several tens of million years. Its growth was punctuated by collision with a Mars-sized impactor that formed the Moon at 30–150 Myr after solar system birth. Whenever collisions occurred, debris was produced. The red dashed line gives the conditions required for melting and differentiation by  $^{26}\text{Al}$  decay. It is calculated by equating the heat conduction timescale  $\Delta t_{\text{conduction}} = (L/2)^2 \times \rho \times C_p/k$  ( $L$  is the diameter of the object,  $\rho$  is the density,  $C_p$  is the specific heat capacity, and  $k$  is the thermal conductivity) with the timescale for adiabatic melting (from equation 8 of Qin et al. 2008):  $\Delta t_{\text{melting}} = -(1/\lambda) \ln(1 - \lambda C_p \Delta T e^{\lambda t_{\text{accretion}}}/A)$ . ( $\lambda$  is the decay constant of  $^{26}\text{Al}$ ,  $t_{\text{accretion}}$  is the accretion time of the object,  $\Delta T$  is the temperature rise needed to induce melting, and  $A$  is the rate of heat production by  $^{26}\text{Al}$  decay at the birth of the solar system.) Thus, the criterion for  $^{26}\text{Al}$ -induced melting in size  $L$  versus accretion time  $t_{\text{accretion}}$  is  $L = 2\sqrt{-(k/\lambda\rho C_p) \ln(1 - \lambda C_p \Delta T e^{\lambda t_{\text{accretion}}}/A)}$ . All the parameters used in calculation of this curve are from Qin et al. (2008). Objects that are less than a few kilometers ( $< 4$  km) or that formed more than a few million years ( $> 2$  Myr) after solar system birth would not be able to melt and differentiate by  $^{26}\text{Al}$  decay alone (see also Grimm & McSween 1993, Moskovitz & Gaidos 2011). The presence of an insulating regolith would allow planetesimals smaller than 4 km to melt.

is also amenable to remote observation through the mid-infrared emission from dust produced by catastrophic collisions between embryos and protoplanets (Lisse et al. 2009, Melis et al. 2010). For example, Melis et al. (2010) were able to detect mid-infrared excess emission from a  $\sim 80$ -Myr-old Sun-like star (HD 15407).

## 8. CONCLUSION

Astronomical observations of nascent stars and protoplanetary disks have made tremendous progress in the past decade. They provide insights into the birth of Sun-like stellar systems that complement the vast knowledge already gained by studying the geochemistry of meteorites and terrestrial planets. In this review, we have tried to present how extinct radionuclides can help us understand how the architecture of the solar system was established (**Figure 9**). They are particularly good tracers because they can measure time, work as dosimeters of early solar activity, and give us clues about the context of solar system formation. Future observations of Earth-like extrasolar planets will tell us if the processes and timescales inferred for the solar system also apply to other stellar systems or if we live in a unique place.

### SUMMARY POINTS

1. The presence of very short-lived nuclides such as  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  suggests that the Sun was probably born in a stellar nursery, near massive stars that seeded the young solar system with newly produced radionuclides.
2. For cosmochemists, the clock started ticking when refractory dusts condensed in the inner part of the disk. This corresponds to the transition between class I and II stellar sources.
3. Study of refractory inclusions indicates that micrometer-sized dust agglomerated into millimeter- to centimeter-sized aggregates in less than 50 kyr. This very short timescale is consistent with dust agglomeration timescales inferred from theory and experiments as well as observations of pre-main sequence stars in the mid-infrared. The presence of  $^{10}\text{Be}$  in these inclusions testifies that these objects formed when the Sun was a T-Tauri star.
4. Millimeter- to centimeter-sized dust was abundant in the disk for the first 4 million years of solar system history. Meteorites were found to contain both refractory inclusions and chondrules that formed several million years afterward. This indicates that particles of different ages coexisted in the disk at any given time.
5. Theory tells us that fragmentation and bouncing should prevent meter-sized objects from growing further. Dating of meteorites shows that planetesimals  $\sim 10$  to 100 km in size formed during the whole lifetime of the protoplanetary disk. The fact that no primary planetesimal is found later than 4 Myr after solar system formation suggests that this time corresponds to dissipation of the gas, marking the transition between a class III stellar source and the debris disk.
6. The planetesimals that formed early (within  $\sim 2$  Myr of solar system formation) and were sufficiently big (more than  $\sim 4$  km) were differentiated by the energy released by  $^{26}\text{Al}$  decay. Those formed more than  $\sim 2$  Myr after solar system formation did not incorporate enough  $^{26}\text{Al}$  to induce melting, and those below  $\sim 4$  km lost their heat by conduction and were never differentiated (unless they were covered by an insulating regolith).

7. Planetesimals grew by runaway and oligarchic growth into planetary embryos. Mars could be such a stranded embryo, and its accretion timescale of  $\sim 2$  Myr is entirely consistent with this idea.
8. Earth's accretion had to proceed by chaotic growth and took several tens of million years to complete. It was punctuated by the Moon-forming impact between a Mars-sized embryo and the proto-Earth at 30–150 Myr after solar system birth, which is broadly consistent with the observation of collisional dust in debris disks as old as  $\sim 80$  Myr.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

## ACKNOWLEDGMENTS

We thank Eric Quirico, Fred Ciesla, Alessandro Morbidelli, and Reika Yokochi for discussions. Comments from Mark Harrison, Kevin McKeegan, Ming Chang Liu, Ritesh Mishra, Paul Craddock, Thomas Ireland, and undergraduate students from the University of Chicago (Cosmochronology, GEOS 22100) helped improve the quality of the manuscript and were greatly appreciated. This work was supported by a fellowship from the David and Lucile Packard Foundation, the France Chicago Center at the University of Chicago, the National Aeronautics and Space Administration, and the National Science Foundation through grants NNX09AG59G and EAR-0820807 to N.D., and by L'Agence Nationale de la Recherche (ANR grant 08-BLAN-0260-02-T-TauriChem) and the European Research Council under the European Community's Seventh Framework Programme (ERC grant FP7/2007-2013 Grant Agreement #226846) to M.C.

## LITERATURE CITED

- Adachi I, Hayashi C, Nakazawa K. 1976. Gas drag effect on elliptic motion of a solid body in primordial solar nebula. *Prog. Theor. Phys.* 56:1756–71
- Adams FC. 2010. The birth environment of the solar system. *Annu. Rev. Astron. Astrophys.* 48:47–85
- Alexander R. 2008. From discs to planetesimals: evolution of gas and dust discs. *New Astron. Rev.* 52:60–77
- Allègre CJ, Dupré B, Brévert O. 1982. Chemical aspects of the formation of the core. *Philos. Trans. R. Soc. A* 306:49–59
- Allègre CJ, Manhès G, Göpel C. 1995. The age of the Earth. *Geochim. Cosmochim. Acta* 59:1445–56
- Allègre CJ, Manhès G, Göpel C. 2008. The major differentiation of the Earth at  $\sim 4.45$  Ga. *Earth Planet. Sci. Lett.* 267:386–98
- Amelin Y. 2008. The U–Pb systematics of angrite Sahara 99555. *Geochim. Cosmochim. Acta* 72:4874–85
- Amelin Y, Kaltenbach A, Iizuka T, Stirling CH, Ireland TR, et al. 2010. U–Pb chronology of the Solar System's oldest solids with variable  $^{238}\text{U}/^{235}\text{U}$ . *Earth Planet. Sci. Lett.* 300:343–50
- Amelin Y, Krot AN, Hutcheon ID, Ulyanov AA. 2002. Lead isotopic ages of chondrules and calcium–aluminum–rich inclusions. *Science* 297:1678–83
- André P. 2002. The initial conditions for protostellar collapse: observational constraints. In *Star Formation and the Physics of Young Stars*, ed. J Bouvier, JP Zahn, pp. 1–38. Les Ulis, Fr.: EDP Sci.
- Arevalo R Jr, McDonough WF. 2008. Tungsten geochemistry and implications for understanding the Earth's interior. *Earth Planet. Sci. Lett.* 272: 656–65
- Baker J, Bizzarro M, Wittig N, Connelly J, Haack H. 2005. Early planetesimal melting from an age of 4.5662 Gyr for differentiated meteorites. *Nature* 436:1127–31

- Baker RGA, Schönbachler M, Rehkämper M, Williams HM, Halliday AN. 2010. The thallium isotope composition of carbonaceous chondrites—new evidence for live  $^{205}\text{Pb}$  in the early solar system. *Earth Planet. Sci. Lett.* 291:39–47
- Basu A, Hart S, eds. 1996. *Earth Processes: Reading the Isotopic Code*. Geophys. Monogr. 95. Washington, DC: AGU. 437 pp.
- Becker H, Walker RJ. 2003. In search of extant Tc in the early solar system:  $^{98}\text{Ru}$  and  $^{99}\text{Ru}$  abundances in iron meteorites and chondrites. *Chem. Geol.* 196:43–56
- Birck J-L, Allègre CJ. 1985. Evidence for the presence of  $^{53}\text{Mn}$  in the early solar system. *Geophys. Res. Lett.* 12:745–48
- Birck J-L, Allègre CJ. 1988. Manganese-chromium isotope systematics and the development of the early solar system. *Nature* 331:579–84
- Birck J-L, Lugmair GW. 1988. Nickel and chromium isotopes in Allende inclusions. *Earth Planet. Sci. Lett.* 90: 131–43
- Bizzarro M, Baker JA, Haack H, Lundgaard KL. 2005. Rapid timescales for accretion and melting of differentiated planetesimals inferred from  $^{26}\text{Al}$ - $^{26}\text{Mg}$  chronometry. *Astrophys. J.* 632:L41–44
- Blum J, Wurm G. 2008. The growth mechanisms of macroscopic bodies in protoplanetary disks. *Annu. Rev. Astron. Astrophys.* 46:21–56
- Bogard DD, Johnson P. 1983. Martian gases in an Antarctic meteorite? *Science* 221:651–54
- Boss AP. 1998. Temperatures in protoplanetary disks. *Annu. Rev. Earth Planet. Sci.* 26:53–80
- Boss AP. 2007. Evolution of the solar nebula. VIII. Spatial and temporal heterogeneity of short-lived radioisotopes and stable oxygen isotopes. *Astrophys. J.* 660:1707–14
- Boss AP, Ipatov SI, Keiser SA, Myhill EA, Vanhala HAT. 2008. Simultaneous triggered collapse of the presolar dense cloud core and injection of short-lived radioisotopes by a supernova shock wave. *Astrophys. J.* 686:L119–22
- Botke WF, Nesvorný D, Grimm RE, Morbidelli A, O'Brien DP. 2006. Iron meteorites as remnants of planetesimals formed in the terrestrial planet region. *Nature* 439:821–24
- Bourdon B, Touboul M, Caro G, Kleine T. 2008. Early differentiation of the Earth and the Moon. *Philos. Trans. R. Soc. A* 366:4105–28
- Bouvier A, Blichert-Toft J, Moynier F, Vervoort JD, Albarede F. 2007. Pb-Pb dating constraints on the accretion and cooling history of chondrites. *Geochim. Cosmochim. Acta* 71:1583–604
- Bouvier A, Wadhwa M. 2010. The age of the Solar System redefined by the oldest Pb-Pb age of a meteoritic inclusion. *Nat. Geosci.* 3:637–41
- Bouwman J, Meeus G, de Koter A, Hony S, Dominik C, Waters LBFM. 2001. Processing of silicate dust grains in Herbig Ae/Be systems. *Astron. Astrophys.* 375:950–62
- Boyet M, Carlson RW, Horan M. 2010. Old Sm-Nd ages for cumulate eucrites and redetermination of the solar system initial  $^{146}\text{Sm}/^{144}\text{Sm}$  ratio. *Earth Planet. Sci. Lett.* 291:172–81
- Brazzle RH, Pravdivtseva OV, Meshik AP, Hohenberg CM. 1999. Verification and interpretation of the I-Xe chronometer. *Geochim. Cosmochim. Acta* 63:739–60
- Brennecka GA, Weyer S, Wadhwa M, Janney PE, Zipfel J, Anbar AD. 2010.  $^{238}\text{U}/^{235}\text{U}$  variations in meteorites: extant  $^{247}\text{Cm}$  and implications for Pb-Pb dating. *Science* 327:449–51
- Burkhardt C, Kleine T, Bourdon B, Palme H, Zipfel J, et al. 2008. Hf-W mineral isochron for Ca,Al-rich inclusions: age of the solar system and the timing of core formation in planetesimals. *Geochim. Cosmochim. Acta* 72:6177–97
- Caffee MW, Hohenberg CM, Swindle TD, Goswami JN. 1987. Evidence in meteorites for an active early sun. *Astrophys. J.* 313:L31–35
- Calvet N, D'Alessio P, Hartmann L, Wilner D, Walsh A, Sitko M. 2002. Evidence for a developing gap in a 10 Myr old protoplanetary disk. *Astrophys. J.* 568:1008–16
- Cameron AGW, Truran JW. 1977. The supernova trigger for formation of the solar system. *Icarus* 30:447–61
- Canup RM, Asphaug E. 2001. Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature* 412:708–12
- Carlson RW, Lugmair GW. 1988. The age of ferroan anorthosite 60025: oldest crust on a young Moon? *Earth Planet. Sci. Lett.* 90:119–30

- Chabot NL, Haack H. 2006. Evolution of asteroidal cores. See Lauretta & McSween 2006, pp. 747–71
- Chambers JE. 2001. Making more terrestrial planets. *Icarus* 152:205–24
- Chambers JE. 2004. Planetary accretion in the inner Solar System. *Earth Planet. Sci. Lett.* 223:241–52
- Chambers JE. 2010. Planetesimal formation by turbulent concentration. *Icarus* 208:505–17
- Chambers JE, Cassen P. 2002. The effects of nebula surface density profile and giant-planet eccentricities on planetary accretion in the inner solar system. *Meteorit. Planet. Sci.* 37:1523–40
- Chambers JE, Wetherill GW. 1998. Making the terrestrial planets: N-body integrations of planetary embryos in three dimensions. *Icarus* 136:304–27
- Chaussidon M, Gounelle M. 2006. Irradiation processes in the early solar system. See Lauretta & McSween 2006, pp. 323–39
- Chaussidon M, Gounelle M. 2007. Short-lived radioactive nuclides in meteorites and early solar system processes. *C.R. Geosci.* 339:872–84
- Chaussidon M, Robert F. 1995. Nucleosynthesis of  $^{11}\text{B}$ -rich boron in the pre-solar cloud recorded in meteoritic chondrules. *Nature* 374:337–39
- Chaussidon M, Robert F. 1998.  $^7\text{Li}/^6\text{Li}$  and  $^{11}\text{B}/^{10}\text{B}$  variations in chondrules from the Semarkona unequilibrium chondrite. *Earth Planet. Sci. Lett.* 164:577–89
- Chaussidon M, Robert F, McKeegan KD. 2006. Li and B isotopic variations in an Allende CAI: evidence for the in situ decay of short-lived  $^{10}\text{Be}$  and for the possible presence of the short-lived nuclide  $^7\text{Be}$  in the early solar system. *Geochim. Cosmochim. Acta* 70:224–45
- Chen JH, Wasserburg GJ. 1996. Live  $^{107}\text{Pd}$  in the early solar system and implications for planetary evolution. See Basu & Hart 1996, pp. 1–20
- Chiang E, Youdin AN. 2010. Forming planetesimals in solar and extrasolar nebulae. *Annu. Rev. Earth Planet. Sci.* 38:493–522
- Chmeleff J, von Blanckenburg F, Kossert K, Jakob D. 2010. Determination of the  $^{10}\text{Be}$  half-life by multicollector ICP-MS and liquid scintillation counting. *Nucl. Instrum. Methods Phys. Res. B* 262:192–199
- Christophe Michel-Lévy M. 1968. Un chondre exceptionnel dans la météorite de Vigarano. *Bull. Soc. Fr. Minéral. Cristallogr.* 91:212–14
- Ciesla FJ. 2007. Outward transport of high-temperature materials around the midplane of the solar nebula. *Science* 318:613–15
- Ciesla FJ. 2010. The distributions and ages of refractory objects in the solar nebula. *Icarus* 208:455–67
- Ciesla FJ, Hood LL. 2002. The nebular shock wave model for chondrule formation: shock processing in a particle-gas suspension. *Icarus* 158:281–93
- Cieza L, Padgett DL, Stapelfeldt KR, Augereau J-C, Harvey P, et al. 2007. The *Spitzer* c2d survey of weak-line T Tauri stars: II. New constraints on the timescale for planet building. *Astrophys. J.* 667:308–28
- Clayton DD. 1988. Nuclear cosmochronology within analytic models of the chemical evolution of the solar neighborhood. *MNRAS* 234:1–36
- Clayton RN. 2002. Self-shielding in the solar nebula. *Nature* 415:860–61
- Clayton RN. 2007. Isotopes: from Earth to the Solar System. *Annu. Rev. Earth Planet. Sci.* 35:1–19
- Clayton RN, Grossman L, Mayeda TK. 1973. A component of primitive nuclear composition in carbonaceous meteorites. *Science* 182:485–88
- Clayton RN, Mayeda TK. 1977. Correlated oxygen and magnesium isotope anomalies in Allende inclusions: I. Oxygen. *Geophys. Res. Lett.* 4:295–98
- Cox LP, Lewis JS. 1980. Numerical simulation of the final stages of terrestrial planet formation. *Icarus* 44:706–21
- Cuzzi JN, Alexander CMO'D. 2006. Chondrule formation in particle-rich nebular regions at least hundreds of kilometers across. *Nature* 441:483–85
- Cuzzi JN, Hogan RC, Shariff K. 2008. Toward planetesimals: dense chondrule clumps in the protoplanetary nebula. *Astrophys. J.* 687:1432–47
- Cuzzi JN, Weidenschilling SJ. 2006. Particle-gas dynamics and primary accretion. See Lauretta & McSween 2006, pp. 353–81
- Dahl TW, Stevenson DJ. 2010. Turbulent mixing of metal and silicate during planetary accretion—an interpretation of the Hf-W chronometer. *Earth Planet. Sci. Lett.* 295:177–86

- D'Alessio P, Calvert N, Woolum DS. 2005. Thermal structure of protoplanetary disks. See Krot et al. 2005c, pp. 353–72
- Das JP, Goswami JN, Pravdivtseva OV, Meshik AP, Hohenberg CM. 2010. Cosmogenic neon in individual chondrule fragments: records of precompaction exposure. *Proc. Lunar Planet. Sci. Conf., 41st, The Woodlands, Tex., March 1–5*, p. 1961. Houston: Lunar Planet. Inst.
- Dauphas N. 2003. The dual origin of the terrestrial atmosphere. *Icarus* 165:326–39
- Dauphas N, Cook DL, Sacarabany A, Fröhlich C, Davis AM, et al. 2008. Iron 60 evidence for early injection and efficient mixing of stellar debris in the protosolar nebula. *Astrophys. J.* 686:560–69
- Dauphas N, Marty B, Reisberg L. 2002a. Inference on terrestrial genesis from molybdenum isotope systematics. *Geophys. Res. Lett.* 29(6):1084
- Dauphas N, Marty B, Reisberg L. 2002b. Molybdenum evidence for inherited planetary scale isotope heterogeneity of the protosolar nebula. *Astrophys. J.* 565:640–44
- Dauphas N, Pourmand 2011. Hf-W-Th evidence for rapid growth of Mars and clues on the birth of an oligarch. *Nature*. In press
- Dauphas N, Remusat L, Chen JH, Roskosz M, Papanastassiou DA, et al. 2010. Neutron-rich chromium isotope anomalies in supernova nanoparticles. *Astrophys. J.* 720:1577–91
- Davis AM, ed. 2005. *Meteorites, Comets, and Planets*. Treatise Geochem. Vol. 1. Oxford: Elsevier-Pergamon. 737 pp.
- Desch SJ, Connolly HC Jr. 2002. A model of the thermal processing of particles in solar nebula shocks: application to the cooling rates of chondrules. *Meteorit. Planet. Sci.* 37:183–207
- Diehl R, Halloin H, Kretschmer K, Lichti GG, Schönfelder V, et al. 2006. Radioactive  $^{26}\text{Al}$  from massive stars in the galaxy. *Nature* 439:45–47
- Dominik CP, Blum J, Cuzzi JN, Wurm G. 2007. Growth of dust as the initial step toward planet formation. See Reipurth et al. 2007, pp. 783–800
- Dubrulle B, Morfill G, Sterzik M. 1994. The dust sub-disk in the protoplanetary nebula. *Icarus* 114:237–46
- Dullemond CP, Dominik C. 2005. Dust coagulation in protoplanetary disks: a rapid depletion of small grains. *Astron. Astrophys.* 434:971–86
- Duprat J, Tatischeff V. 2007. Energetic constraints on in situ production of short-lived radionuclides in the early solar system. *Astrophys. J.* 671:L69–72
- Duprat J, Tatischeff V. 2008. On nonthermal nucleosynthesis of short-lived radionuclides in the early solar system. *New Astron. Rev.* 52:463–66
- Fehr MA, Rehkämper M, Halliday AN, Schönbächler M, Hattendorf B, Günther D. 2006. Search for nucleosynthetic and radiogenic tellurium isotope anomalies in carbonaceous chondrites. *Geochim. Cosmochim. Acta* 70:3436–48
- Feigelson ED, Garmire GP, Pravdo SH. 2002. Magnetic flaring in the pre-main-sequence Sun and implications for the early solar system. *Astrophys. J.* 572:335–49
- Feigelson ED, Montmerle T. 1999. High-energy processes in young stellar objects. *Annu. Rev. Astron. Astrophys.* 37:363–408
- Foley CN, Wadhwa M, Borg LE, Janney PE, Hines R, Grove TL. 2005. The early differentiation history of Mars from  $^{182}\text{W}$ - $^{142}\text{Nd}$  isotope systematics in the SNC meteorites. *Geochim. Cosmochim. Acta* 69:4557–71
- Galer SJG, Goldstein SL. 1996. Influence of accretion on lead in the Earth. See Basu & Hart 1996, pp. 75–98
- Ghosh A, Weidenschilling SJ, McSween HY Jr, Rubin A. 2006. Asteroidal heating and thermal stratification of the asteroid belt. See Lauretta & McSween 2006, pp. 555–65
- Goldreich P, Lithwick Y, Sari R. 2004. Final stages of planet formation. *Astrophys. J.* 614:497–507
- Goldreich P, Ward WR. 1973. Formation of planetesimals. *Astrophys. J.* 183:1051–61
- Goswami JN, Marhas KK, Sahijpal S. 2001. Did solar energetic particles produce the short-lived nuclides present in the early solar system? *Astrophys. J.* 549:1151–59
- Gounelle M, Meibom A, Hennebelle P, Inutsuka S-I. 2009. Supernova propagation and cloud enrichment: a new model for the origin of  $^{60}\text{Fe}$  in the early solar system. *Astrophys. J.* 694:L1–5
- Gounelle M, Shu FH, Hsien S, Glassgold AE, Rehm KE, Lee T. 2006. The irradiation origin of beryllium radioisotopes and other short-lived radionuclides. *Astrophys. J.* 640:1163–70
- Gounelle M, Shu FH, Shang H, Glassgold AE, Rehm KE, Lee T. 2001. Extinct radioactivities and protosolar cosmic rays: self-shielding and light elements. *Astrophys. J.* 548:1051–70

- Gounelle M, Young ED, Shahar A, Tonui A, Kearsley A. 2007. Magnesium isotopic constraints on the origin of CB<sub>6</sub> chondrites. *Earth Planet. Sci. Lett.* 256:521–33
- Gray CM, Compston W. 1974. Excess <sup>26</sup>Mg in the Allende meteorite. *Nature* 251:495–97
- Greenberg R, Wacker JF, Hartmann WK, Chapman CR. 1978. Planetesimals to planets: numerical simulation of collisional evolution. *Icarus* 35:1–26
- Grimm RE, McSween HY Jr. 1993. Heliocentric zoning of the asteroid belt by aluminum-26 heating. *Science* 259:653–55
- Grossman L. 1972. Condensation in primitive solar nebula. *Geochim. Cosmochim. Acta* 36:597–619
- Grossman L, Ebel DS, Simon SB, Davis AM, Richter FM, Parsad NM. 2000. Major element chemical and isotopic compositions of refractory inclusions in C3 chondrites: the separate roles of condensation and evaporation. *Geochim. Cosmochim. Acta* 64:2879–94
- Grossman L, Larimer JW. 1974. Early chemical history of the solar system. *Rev. Geophys.* 12:71–101
- Haghighipour N, Boss AP. 2003. On pressure gradients and rapid migration of solids in a nonuniform solar nebula. *Astrophys. J.* 583:996–1003
- Halliday A, Rehkämper M, Lee D-C, Yi W. 1996. Early evolution of the Earth and Moon: new constraints from Hf-W isotope geochemistry. *Earth Planet. Sci. Lett.* 142:75–89
- Halliday AN. 2004. Mixing, volatile loss and compositional change during impact-driven accretion of the Earth. *Nature* 427:505–9
- Harper CL. 1996. Evidence for <sup>92</sup>Nb in the early solar system and evaluation of a new p-process cosmochronometer from <sup>92</sup>Nb/<sup>92</sup>Mo. *Astrophys. J.* 466:437–56
- Harrison TM. 2009. The Hadean crust: evidence from >4 Ga zircons. *Annu. Rev. Earth Planet. Sci.* 37:479–505
- Hevey PJ, Sanders IS. 2006. A model for planetesimal meltdown by <sup>26</sup>Al and its implications for meteorite parent bodies. *Meteorit. Planet. Sci.* 41:95–106
- Heymann D, Dziczkaniec M. 1976. Early irradiation of matter in the solar system: magnesium (proton, neutron) scheme. *Science* 191:79–81
- Hidaka H, Ohta Y, Yoneda S, DeLaeter JR. 2001. Isotopic search for live <sup>135</sup>Cs in the early solar system and possibility of <sup>135</sup>Cs-<sup>135</sup>Ba chronometer. *Earth Planet. Sci. Lett.* 193:459–66
- Hohenberg CM, Nichols RHJ, Olinger CT, Goswami JN. 1990. Cosmogenic neon from individual grains of CM meteorites: extremely long precompaction histories or an enhanced early particle flux. *Geochim. Cosmochim. Acta* 54:2133–40
- Hollenbach DJ, Yorke HW, Johnstone D. 2000. Disk dispersal around young stars. In *Protostars and Planets IV*, ed. W Mannings, AP Boss, SS Russell, pp. 401–28. Tucson, AZ: Univ. Ariz. Press
- Hood LL, Horanyi M. 1993. The nebular shock wave model for chondrule formation: one-dimensional calculations. *Icarus* 106:179–89
- Hsu WB, Guan Y, Leshin LA, Ushikubo T, Wasserburg GJ. 2006. A late episode of irradiation in the early solar system: evidence from extinct <sup>36</sup>Cl and <sup>26</sup>Al in meteorites. *Astrophys. J.* 640:525–29
- Hsu WB, Huss GR, Wasserburg GJ. 2003. Al-Mg systematics of CAIs, POI, and ferromagnesian chondrules from Ningqiang. *Meteorit. Planet. Sci.* 38:35–48
- Hudson GB, Kennedy BM, Podosek FA, Hohenberg CM. 1989. The early solar system abundance of Pu-244 as inferred from the St. Severin chondrite. *Proc. Lunar Planet. Sci. Conf., 19th, Houston, March 14–18*, pp. 547–57. Houston: Lunar Planet. Inst.
- Hunten DM, Pepin RO, Walker JCG. 1987. Mass fractionation in hydrodynamic escape. *Icarus* 69:532–49
- Huss GR, Hutcheon ID, Wasserburg GJ. 1997. Isotopic systematics of presolar silicon carbide from the Orgueil (CI) chondrite: implications for solar system formation and stellar nucleosynthesis. *Geochim. Cosmochim. Acta* 61:5117–48
- Hutcheon ID, Hutchison R. 1989. Evidence from the Semarkona ordinary chondrite for <sup>26</sup>Al heating of small planets. *Nature* 337:238–41
- Hutcheon ID, Krot AN, Ulyanov AA. 2000. <sup>26</sup>Al in anorthite-rich chondrules in primitive carbonaceous chondrites: evidence chondrules postdate CAI. *Proc. Lunar Planet. Sci. Conf., 31st, Houston, March 13–17*, Abstr. 1869. Houston: Lunar Planet. Inst.
- Ida S, Makino J. 1993. Scattering of planetesimals by a protoplanet: slowing down of runaway growth. *Icarus* 106:210–27

- Jacobsen B, Matzel J, Hutcheon ID, Ramon E, Krot AN, et al. 2009. The  $^{36}\text{Cl}$ - $^{36}\text{S}$  systematics of wadalite from the Allende meteorite. *Proc. Lunar Planet. Sci. Conf., 40th, The Woodlands, Tex., March 23–27*, Abstr. 2553. Houston: Lunar Planet. Inst.
- Jacobsen B, Yin Q-Z, Moynier F, Amelin Y, Krot AN, et al. 2008.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  and  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  systematics of Allende CAIs: canonical solar initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio reinstated. *Earth Planet. Sci. Lett.* 272:353–64
- Jacobsen SB. 2005. The Hf-W isotopic system and the origin of the Earth and Moon. *Annu. Rev. Earth Planet. Sci.* 33:531–70
- Jacobsen SB, Harper CL Jr. 1996. Accretion and early differentiation history of the Earth based on extinct radionuclides. See Basu & Hart 1996, pp. 47–74
- Jeffery PM, Reynolds JH. 1961. Origin of excess  $\text{Xe}^{129}$  in stone meteorites. *J. Geophys. Res.* 66:3582–83
- Johansen A, Oishi JS, Mac Low MM, Klahr H, Henning T, Youdin A. 2007. Rapid planetesimal formation in turbulent circumstellar disks. *Nature* 448:1022–25
- Kastner JH, Myers PC. 1994. An observational estimate of the probability of encounters between mass-losing evolved stars and molecular clouds. *Astrophys. J.* 421:605–15
- Kenyon SJ, Bromley BC. 2006. Terrestrial planet formation: I. The transition from oligarchic growth to chaotic growth. *Astron. J.* 131:1837–50
- Kessler-Silacci J, Augereau JC, Dullemond CP, Geers V, Lahuis F, et al. 2006. c2d *Spitzer* IRS spectra of disks around T Tauri stars: I. Silicate emission and grain growth. *Astrophys. J.* 639:275–91
- Kita NT, Huss GR, Tachibana S, Amelin Y, Nyquist LE, Hutcheon ID. 2005a. Constraints on the origin of chondrules and CAIs from short-lived and long-lived radionuclides. See Krot et al. 2005c, pp. 558–87
- Kita NT, Nagahara H, Togashi S, Morishita Y. 2000. A short duration of chondrule formation in the solar nebula: evidence from  $^{26}\text{Al}$  in Semarkona ferromagnesian chondrules. *Geochim. Cosmochim. Acta* 64:3913–22
- Kita NT, Tomomura S, Tachibana S, Nagahara H, Mostéfaoui S. 2005b. Correlation between aluminium-26 ages and bulk Si/Mg ratios for chondrules from LL3.0-3.1 chondrites. *Proc. Lunar Planet. Sci. Conf., 36th, League City, Tex., March 14–18*, Abstr. 1750. Houston: Lunar Planet. Inst.
- Kleine T, Mezger K, Palme H, Scherer E, Münker C. 2005. Early core formation in asteroids and late accretion of chondrite parent bodies: evidence from  $^{182}\text{Hf}$ - $^{182}\text{W}$  in CAIs, metal-rich chondrites and iron meteorites. *Geochim. Cosmochim. Acta* 69:5805–18
- Kleine T, Münker C, Mezger K, Palme H. 2002. Rapid accretion and early core formation on asteroids and the terrestrial planets from Hf-W chronometry. *Nature* 418:952–55
- Kleine T, Touboul M, Bourdon B, Nimmo F, Mezger K, et al. 2009. Hf-W chronology of the accretion and early evolution of asteroids and terrestrial planets. *Geochim. Cosmochim. Acta* 73:5150–88
- Kleine T, Touboul M, Palme H, Zipfel J, Halliday AN. 2007. Cosmochemical fractionation of Hf and W in the solar nebula: evidence from W isotopes in chondrites. *Proc. Lunar Planet. Sci. Conf., 38th, League City, Tex., March 12–16*, Abstr. 2362. Houston: Lunar Planet. Inst.
- Kokubo E, Ida S. 1998. Oligarchic growth of protoplanets. *Icarus* 131:171–78
- Kokubo E, Ida S. 2000. Formation of protoplanets from planetesimals in the solar nebula. *Icarus* 143:15–27
- König S, Münker C, Hohl S, Paulick H, Barth AR, et al. 2011. The Earth's tungsten budget during mantle melting and crust formation. *Geochim. Cosmochim. Acta* 75:2119–36
- Krot AN, Amelin Y, Cassen P, Meibom A. 2005a. Young chondrules in CB chondrites from a giant impact in the early Solar system. *Nature* 436:989–92
- Krot AN, Keil K, Goodrich CA, Scott ERD, Weisberg MK. 2005b. Classification of meteorites. See Davis 2005, pp. 83–128
- Krot AN, Scott ERD, Reipurth B, eds. 2005c. *Chondrites and the Protoplanetary Disk*. ASP Conf. Ser. 341. San Francisco: Astron. Soc. Pac. 1029 pp.
- Kunihiro T, Rubin AE, McKeegan KD, Wasson JT. 2004. Initial  $^{26}\text{Al}/^{27}\text{Al}$  in carbonaceous-chondrite chondrules: too little  $^{26}\text{Al}$  to melt asteroids. *Geochim. Cosmochim. Acta* 68:2947–57
- Kurahashi E, Kita NT, Nagahara H, Morishita Y. 2008.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics of chondrules in a primitive CO chondrite. *Geochim. Cosmochim. Acta* 72:3865–82
- Kwon W, Looney LW, Mundy LG, Chiang H-F, Kemball AJ. 2009. Grain growth and density distribution of the youngest protostellar systems. *Astrophys. J.* 696:841–52

- Lada CJ, Lada EA. 2003. Embedded clusters in molecular clouds. *Annu. Rev. Astron. Astrophys.* 41:57–115
- Lagrange AM, Bonnefoy M, Chauvin G, Apai D, Ehrenreich D, et al. 2010. A giant planet imaged in the disk of the young star  $\beta$  Pictoris. *Science* 329:57–59
- LaTourrette T, Wasserburg GJ. 1998. Mg diffusion in anorthite: implications for the formation of early solar system planetesimals. *Earth Planet. Sci. Lett.* 158:91–108
- Lauretta DS, McSween HY Jr, eds. 2006. *Meteorites and the Early Solar System II*. Tucson, AZ: Univ. Ariz. Press. 943 pp.
- Lee DC, Halliday AN. 1995. Hafnium-tungsten chronometry and the timing of terrestrial core formation. *Nature* 378:771–74
- Lee DC, Halliday AN. 1997. Core formation on Mars and differentiated asteroids. *Nature* 388:854–57
- Lee DC, Halliday AN. 2000. Accretion of primitive planetesimals: Hf-W isotopic evidence from enstatite chondrites. *Science* 288:1629–31
- Lee T, Papanastassiou DA, Wasserburg GJ. 1976. Demonstration of  $^{26}\text{Mg}$  excess in Allende and evidence for  $^{26}\text{Al}$ . *Geophys. Res. Lett.* 3:109–12
- Lee T, Papanastassiou DA, Wasserburg GJ. 1977. Aluminum-26 in early solar system—fossil or fuel. *Astrophys. J.* 211:L107–10
- Lee T, Shu FH, Shang H, Glassgold AE, Rhem KE. 1998. Protostellar cosmic rays and extinct radioactivities in meteorites. *Astrophys. J.* 506:898–912
- Levison HF, Agnor C. 2003. The role of giant planets in terrestrial planet formation. *Astron. J.* 125:2692–713
- Leya I, Wieler R, Halliday AN. 2003. The influence of cosmic-ray production on extinct nuclide systems. *Geochim. Cosmochim. Acta* 67:529–41
- Libourel G, Chaussidon M. 2011. Oxygen isotopic constraints on the origin of Mg-rich olivines from chondritic meteorites. *Earth Planet. Sci. Lett.* 301:9–21
- Libourel G, Krot AN. 2007. Evidence for the presence of planetesimal material among the precursors of magnesian chondrules of nebular origin. *Earth Planet. Sci. Lett.* 254:1–8
- Lin Y, Guan Y, Leshin LA, Ouyang Z, Wang D. 2005. Short-lived chlorine-36 in a Ca- and Al-rich inclusion from the Ningqiang carbonaceous chondrite. *Proc. Natl. Acad. Sci. USA* 102:1306–11
- Lisse CM, Chen CH, Wyatt MC, Morlok A, Song I, et al. 2009. Abundant circumstellar silica dust and SiO gas created by a giant hypervelocity collision in the  $\sim 12$  Myr HD172555 system. *Astrophys. J.* 701:2019–33
- Liu M-C, McKeegan KD, Goswami JN, Marhas KK, Sahijpal S, et al. 2009. Isotopic records in CM hibonites: implications for timescales of mixing of isotope reservoirs in the solar nebula. *Geochim. Cosmochim. Acta* 73:5051–79
- Liu M-C, Nittler LR, Alexander CMO'D, Lee T. 2010. Lithium-beryllium-boron isotopic compositions in meteoritic hibonite: implications for origin of  $^{10}\text{Be}$  and early solar system irradiation. *Astrophys. J.* 719:L99–103
- Lodders K, Fegley B. 1997. An oxygen isotope model for the composition of Mars. *Icarus* 126:373–94
- Lommen DJP, van Dishoeck EF, Wright CM, Maddison ST, Min M, et al. 2010. Grain growth across protoplanetary discs: 10  $\mu\text{m}$  silicate feature versus millimeter slope. *Astron. Astrophys.* 515:A77
- Lugmair GW, Galer SJG. 1992. Age and isotopic relationships among the angrites Lewis Cliff 86010 and Angra dos Reis. *Geochim. Cosmochim. Acta* 56:1673–94
- MacPherson GJ. 2005. Calcium-aluminum-rich inclusions in chondritic meteorites. See Davis 2005, pp. 201–46
- MacPherson GJ, Bullock ES, Janney PE, Kita NT, Ushikubo T, et al. 2010a. Early solar nebula condensates with canonical, not supracanonical, initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios. *Astrophys. J. Lett.* 711:L117–212
- MacPherson GJ, Davis AM, Zinner EK. 1995. The distribution of aluminum-26 in the early Solar System—a reappraisal. *Meteoritics* 30:365–86
- MacPherson GJ, Huss GR, Davis AM. 2003. Extinct  $^{10}\text{Be}$  in type A calcium-aluminum-rich inclusions from CV chondrites. *Geochim. Cosmochim. Acta* 67:3165–79
- MacPherson GJ, Kita NT, Ushikubo T, Bullock ES, Davis AM. 2010b. High precision  $^{26}\text{Al}/^{27}\text{Al}$  isochron microchronology of the earliest solar system. *Proc. Lunar Planet. Sci. Conf., 41st, The Woodlands, Tex., March 1–5*, Abstr. 2356. Houston: Lunar Planet. Inst.
- Makalkin AB, Dorofeeva VA. 2009. Temperature distribution in the solar nebula at successive stages of its evolution. *Solar Syst. Res.* 43:508–32

- Marhas KK, Goswami JN, Davis AM. 2002. Short-lived nuclides in hibonite grains from Murchison: evidence for solar system evolution. *Science* 298:2182–85
- Markowski A, Leya I, Quitté G, Ammon K, Halliday AN, Wieler R. 2006. Correlated helium-3 and tungsten isotopes in iron meteorites: quantitative cosmogenic corrections and planetesimal formation times. *Earth Planet. Sci. Lett.* 250:104–15
- Markowski A, Quitté G, Kleine T, Halliday A, Bizzarro M, Irving AJ. 2007. Hf-W chronometry of angrites and the earliest evolution of planetary bodies. *Earth Planet. Sci. Lett.* 262:214–29
- Mathis JS, Rumpl W, Nordsieck KH. 1977. Size distribution of interstellar grains. *Astrophys. J.* 217:425–33
- Matsuyama I, Johnstone D, Hollenbach D. 2009. Dispersal of protoplanetary disks by central wind stripping. *Astrophys. J.* 700:10–19
- Matzel JEP, Ishii HA, Joswiak D, Hutcheon ID, Bradley JP, et al. 2010. Constraints on the formation age of cometary material from the NASA Stardust mission. *Science* 328:483–86
- McKeegan KD, Aleon J, Bradley J, Brownlee D, Busemann H, et al. 2006. Isotopic compositions of cometary matter returned by Stardust. *Science* 314:1724–28
- McKeegan KD, Chaussidon M, Robert F. 2000. Incorporation of short-lived  $^{10}\text{Be}$  in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science* 289:1334–37
- Melis C, Zuckerman B, Rhee JH, Song I. 2010. The age of the HD 15407 system and the epoch of final catastrophic mass accretion onto terrestrial planets around Sun-like stars. *Astrophys. J. Lett.* 717:L57–61
- Meyer BS, Clayton DD. 2000. Short-lived radioactivities and the birth of the Sun. *Space Sci. Rev.* 92:133–52
- Mishra RK, Goswami JN, Tachibana S, Huss GR, Rudraswami NG. 2010.  $^{60}\text{Fe}$  and  $^{26}\text{Al}$  in chondrules from unequilibrated chondrites: implications for early solar system processes. *Astrophys. J.* 714:L217–21
- Mizuno H. 1980. Formation of the giant planets. *Prog. Theor. Phys.* 64:544–57
- Montmerle T, Augerau J-C, Chaussidon M, Gounelle M, Marty B, Morbidelli A. 2006. Solar system formation and early evolution: the first 100 million years. *Earth Moon Planets* 98:39–95
- Morbidelli A, Bottke WF, Nesvorný D, Levison HF. 2009. Asteroids were born big. *Icarus* 204:558–73
- Morfill GE. 1988. Protoplanetary accretion disks with coagulation and evaporation. *Icarus* 75:371–79
- Moskovitz N, Gaidos E. 2011. Differentiation of planetesimals and the thermal consequences of melt migration. *Meteorit. Planet. Sci.* In press
- Mostéfaoui S, Kita NT, Tachibana S, Nagahara H, Togashi S, Morishita Y. 2000. Correlated initial aluminum-26/aluminum-27 with olivine and pyroxene proportions in chondrules from highly unequilibrated ordinary chondrites. *Meteorit. Planet. Sci.* 35:A114
- Nagashima K, Krot AN, Chaussidon M. 2007. Aluminum-magnesium isotope systematics of chondrules from CR chondrites. *Meteorit. Planet. Sci.* 42:A115
- Nagashima K, Krot AN, Huss GR. 2008.  $^{26}\text{Al}$  in chondrules from CR carbonaceous chondrites. *Proc. Lunar Planet. Sci. Conf., 39th, League City, Tex., March 10–24*, Abstr. 2224. Houston: Lunar Planet. Inst.
- Newsom HE, Sims KWW, Noll PD Jr, Jaeger WL, Maehr SA, Beserra TB. 1996. The depletion of tungsten in the bulk silicate earth: constraints on core formation. *Geochim. Cosmochim. Acta* 60:1155–69
- Nimmo F, Agnor CB. 2006. Isotopic outcomes of N-body accretion simulations: constraints on equilibration processes during large impacts from Hf/W observations. *Earth Planet. Sci. Lett.* 243:26–43
- Nimmo F, Kleine T. 2007. How rapidly did Mars accrete? Uncertainties in the Hf-W timing of core formation. *Icarus* 191:497–504
- Nimmo F, O'Brien DP, Kleine T. 2010. Tungsten isotopic evolution during late-stage accretion: constraints on Earth-Moon equilibration. *Earth Planet. Sci. Lett.* 292:363–70
- Nittler LR, Dauphas N. 2006. Meteorites and the chemical evolution of the Milky Way. See Lauretta & McSween 2006, pp. 147–67
- Norman MD, Borg LE, Nyquist LE, Bogard DD. 2003. Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: clues to the age, origin, structure, and impact history of the lunar crust. *Meteorit. Planet. Sci.* 38:645–61
- O'Brien DP, Morbidelli A, Levison HF. 2006. Terrestrial planet formation with strong dynamical friction. *Icarus* 184:39–58
- Ouellette N, Desch SJ, Hester JJ. 2007. Interaction of supernova ejecta with nearby protoplanetary disks. *Astrophys. J.* 662:1268–81

- Ouellette N, Desch SJ, Hester JJ, Leshin LA. 2005. A nearby supernova injected short-lived radionuclides into our protoplanetary disk. See Krot et al. 2005c, pp. 527–38
- Pahlevan K, Stevenson DJ. 2007. Equilibration in the aftermath of the lunar-forming giant impact. *Earth Planet. Sci. Lett.* 262:438–49
- Pepin RO. 1991. On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles. *Icarus* 92:2–79
- Pollack JB, Hubickyj O, Bodenheimer P, Lissauer JJ, Podolak M, Greenzweig Y. 1996. Formation of the giant planets by concurrent accretion of solids and gas. *Icarus* 124:62–85
- Preibisch T, Feigelson ED. 2005. The evolution of X-ray emission in young stars. *Astrophys. J.* 160:390–400
- Preibisch T, Kim Y-C, Favata F, Feigelson ED, Flaccomio E, et al. 2005. The origin of T Tauri X-ray emission: new insights from the Chandra Orion Ultradeep Project. *Astrophys. J.* 160:401–22
- Prinzhofer A, Papanastassiou DA, Wasserburg GJ. 1992. Samarium-neodymium evolution of meteorites. *Geochim. Cosmochim. Acta* 56:797–815
- Przygodda F, van Boekel R, Abraham P, Melnikov SY, Waters LBFM, Leinert C. 2003. Evidence for grain growth in T Tauri disks. *Astron. Astrophys.* 412:L43–46
- Qin LP, Dauphas N, Wadhwa M, Masarik J, Janney PE. 2008. Rapid accretion and differentiation of iron meteorite parent bodies inferred from  $^{182}\text{Hf}$ - $^{182}\text{W}$  chronometry and thermal modeling. *Earth Planet. Sci. Lett.* 273:94–104
- Quitté G, Halliday AN, Meyer BS, Markowski A, Latkoczy C, Günther D. 2007. Correlated iron 60, nickel 62, and zirconium 96 in refractory inclusions and the origin of the solar system. *Astrophys. J.* 655:678–84
- Quitté G, Markowski A, Latkoczy C, Gabriel A, Pack A. 2010. Iron-60 heterogeneity and incomplete isotope mixing in the early solar system. *Astrophys. J.* 720:1215
- Raymond SN, O'Brien DP, Morbidelli A, Kaib NA. 2009. Building the terrestrial planets: constrained accretion in the inner Solar System. *Icarus* 203:644–62
- Raymond SN, Quinn T, Lunine JI. 2006. High-resolution simulations of the final assembly of Earth-like planets. I: Terrestrial accretion and dynamics. *Icarus* 183:265–82
- Reeves H. 1994. On the origin of the light elements ( $Z < 6$ ). *Rev. Mod. Phys.* 66:193–216
- Reeves H, Fowler W, Hoyle F. 1970. Galactic cosmic ray origin of Li, Be and B in stars. *Nature* 226:727–29
- Reipurth B. 2005. The early sun: evolution and dynamic environment. See Krot et al. 2005c, pp. 54–77
- Reipurth B, Jewitt D, Keil K, eds. 2007. *Protostars and Planets V*. Tucson, AZ: Univ. Ariz. Press. 1024 pp.
- Ricard Y, Šrámek O, Dubuffet F. 2009. A multi-phase model of runaway core-mantle segregation in planetary embryos. *Earth Planet. Sci. Lett.* 284:144–50
- Ricci L, Testi L, Natta A, Neri R, Cabrit S, Herczeg GJ. 2010. Dust properties of protoplanetary disks in the Taurus-Auriga star forming region from millimeter wavelengths. *Astron. Astrophys.* 512:A15
- Richter FM, Mendenybaev RA, Davis AM. 2006. Conditions in the protoplanetary disk as seen by the type B CAIs. *Meteorit. Planet. Sci.* 41:83–93
- Rodmann J, Henning T, Chandler CJ, Mundy LG, Wilner DJ. 2006. Large dust particles in disks around T Tauri stars. *Astron. Astrophys.* 446:211–21
- Rubie DC, Melosh HJ, Reid JE, Liebske C, Righter K. 2003. Mechanisms of metal-silicate equilibration in the terrestrial magma ocean. *Earth Planet. Sci. Lett.* 205:239–55
- Rudraswami NG, Goswami JN. 2007.  $^{26}\text{Al}$  in chondrules from unequilibrated L chondrites: onset and duration of chondrule formation in the early solar system. *Earth Planet. Sci. Lett.* 257:231–44
- Rudraswami NG, Goswami JN, Chattopadhyay B, Sengupta SK, Thapliyal AP. 2008.  $^{26}\text{Al}$  records in chondrules from unequilibrated ordinary chondrites: II. Duration of chondrule formation and parent body thermal metamorphism. *Earth Planet. Sci. Lett.* 274:93–102
- Rugel G, Faestermann T, Knie K, Korschinek G, Poutivtsev M, et al. 2009. New measurement of the  $^{60}\text{Fe}$  half-life. *Phys. Rev. Lett.* 103:072502
- Russell SS, Srinivasan G, Huss GR, Wasserburg GJ, MacPherson GJ. 1996. Evidence for widespread  $^{26}\text{Al}$  in the solar nebula and constraints for nebula time scales. *Science* 273:757–62
- Safronov VS. 1969. *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets*. Moscow: Nauka
- Schiller M, Baker JA, Bizzarro M. 2010.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  dating of asteroidal magmatism in the young Solar System. *Geochim. Cosmochim. Acta* 74:4844–64

- Schoenberg R, Kamber BS, Collerson KD, Eugster O. 2002. New W-isotope evidence for rapid terrestrial accretion and very early core formation. *Geochim. Cosmochim. Acta* 66:3151–60
- Schönbächler M, Carlson RW, Horan MF, Mock TD, Hauri EH. 2008. Silver isotope variations in chondrites: volatile depletion and the initial  $^{107}\text{Pd}$  abundance of the solar system. *Geochim. Cosmochim. Acta* 72:5330–41
- Schönbächler M, Rehkämper M, Halliday AN, Lee DC, Bourot-Denise M, et al. 2002. Niobium-zirconium chronometry and early solar system development. *Science* 295:1705–8
- Sekiya M, Nakazawa K, Hayashi C. 1980. Dissipation of the primordial terrestrial atmosphere due to irradiation of the solar EUV. *Prog. Theor. Phys.* 64:1968–85
- Shu FH, Shang H, Gounelle M, Glassgold AE, Lee T. 2001. The origin of chondrules and refractory inclusions in chondritic meteorites. *Astrophys. J.* 548:1029–50
- Shu FH, Shang H, Lee T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–52
- Shukolyukov A, Lugmair GW. 1993.  $^{60}\text{Fe}$  in eucrites. *Earth Planet. Sci. Lett.* 119:159–66
- Shukolyukov A, Lugmair GW. 2006. Manganese-chromium isotope systematics of carbonaceous chondrites. *Earth Planet. Sci. Lett.* 250:200–13
- Simon SB, Joswiak DJ, Ishii HA, Bradley JP, Chi M, et al. 2008. A refractory inclusion returned by Stardust from comet 81P/Wild 2. *Meteorit. Planet. Sci.* 43:1861–77
- Spivak-Birndorf L, Wadhwa M, Janney P. 2009.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics in D'Orbigny and Sahara 99555 angrites: implications for high-resolution chronology using extinct chronometers. *Geochim. Cosmochim. Acta* 73:5202–5211
- Srinivasan G, Sahijpal S, Ulyanov AA, Goswami JN. 1996. Ion microprobe studies of Efremovka CAIs: II. Potassium isotope composition and  $^{41}\text{Ca}$  in the early solar system. *Geochim. Cosmochim. Acta* 60:1823–35
- Srinivasan G, Ulyanov AA, Goswami JN. 1994.  $^{41}\text{Ca}$  in the early solar system. *Astrophys. J.* 431:L67–70
- Sugiura N, Krot AN. 2007.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics of Ca-Al-rich inclusions, amoeboid olivine aggregates, and chondrules from the ungrouped carbonaceous chondrite Acfer 094. *Meteorit. Planet. Sci.* 42:1183–95
- Sugiura N, Shuzou Y, Ulyanov AA. 2001. Beryllium-boron and aluminum-magnesium chronology of calcium-aluminum-rich inclusions in CV chondrites. *Meteorit. Planet. Sci.* 36:1397–408
- Tachibana S, Huss GR, Kita NT, Shimoda G, Morishita Y. 2006.  $^{60}\text{Fe}$  in chondrites: debris from a nearby supernova in the early solar system? *Astrophys. J.* 639:L87–90
- Takigawa A, Miki J, Tachibana S, Huss GR, Tominaga N, et al. 2008. Injection of short-lived radionuclides into the early solar system from a faint supernova with mixing fallback. *Astrophys. J.* 688:1382–87
- Tang H, Dauphas N. 2011. Constraints from achondrites on the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of the solar system. *Proc. Lunar Planet. Sci. Conf., 42nd, The Woodlands, Tex., March 7–11*, Abstr. 1068. Houston: Lunar Planet. Inst.
- Thrane KB, Bizzarro M, Baker JA. 2006. Extremely brief formation interval for refractory inclusions and uniform distribution of  $^{26}\text{Al}$  in the early solar system. *Astrophys. J.* 646:L159–62
- Touboul M, Kleine T, Bourdon B, Palme H, Wieler R. 2007. Late formation and prolonged differentiation of the Moon inferred from W isotopes in lunar metals. *Nature* 450:1206–9
- Town CC. 2008. *Tracing the origins of refractory inclusions—the Solar System's oldest solids—a petrographic, geochemical and  $^{26}\text{Al}$ - $^{26}\text{Mg}$  dating study of CV and CK refractory inclusions*. PhD thesis. Vic. Univ. Wellingt., N.Z. 155 pp.
- Trieloff M, Jessberger EK, Ingrid H, Hopp J, Fiéni C, et al. 2003. Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronology. *Nature* 422:502–6
- Trinquier A, Birk JL, Allègre CJ, Göpel C, Ulfbeck D. 2008.  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics of the early Solar System revisited. *Geochim. Cosmochim. Acta* 72:5146–63
- Vanhala HAT, Boss AP. 2002. Injection of radioactivities into the forming solar system. *Astrophys. J.* 575:1144–50
- Villeneuve J, Chaussidon M, Libourel G. 2009. Homogeneous distribution of  $^{26}\text{Al}$  in the solar system from Mg isotopic composition of chondrules. *Science* 325:985–88
- Villeneuve J, Chaussidon M, Libourel G. 2011. Magnesium isotopes constraints on the origin of refractory olivines from the Allende chondrite: nebular versus planetary. *Earth Planet. Sci. Lett.* 301:107–116
- Vockenhuber C, Oberli F, Bichler M, Ahmad I, Quitté G, et al. 2004. New half-life measurement of  $^{182}\text{Hf}$ : improved chronometer for the early solar system. *Phys. Rev. Lett.* 93:172501

- Wang W, Harris MJ, Diehl R, Halloin H, Cordier B, et al. 2007. SPI observations of the diffuse  $^{60}\text{Fe}$  emission in the Galaxy. *Astron. Astrophys.* 469:1005–12
- Wasserburg GJ. 1987. Isotopic abundances: inferences on solar system and planetary evolution. *Earth Planet. Sci. Lett.* 86:129–73
- Wasserburg GJ, Busso M, Gallino R, Nollett KM. 2006. Short-lived nuclei in the early Solar System: possible AGB sources. *Nucl. Phys. A* 777:5–69
- Wasserburg GJ, Gallino R, Busso M. 1998. A test of the supernova trigger hypothesis with  $^{60}\text{Fe}$  and  $^{26}\text{Al}$ . *Astrophys. J.* 500:L189–93
- Wasserburg GJ, Lee T, Papanastassiou DA. 1977. Correlated O and Mg isotopic anomalies in Allende inclusions: II. Magnesium. *Geophys. Res. Lett.* 4:299–302
- Weidenschilling SJ. 1977. Aerodynamics of solid bodies in solar nebula. *MNRAS* 180:57–70
- Weidenschilling SJ. 1980. Dust to planetesimals: settling and coagulation in the solar nebula. *Icarus* 44:172–89
- Weidenschilling SJ. 1997. The origin of comets in the solar nebula: a unified model. *Icarus* 127:290–306
- Weingartner JC, Draine BT. 2001. Dust grain-size distributions and extinction in the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud. *Astrophys. J.* 548:296–309
- Wetherill GW. 1975. Radiometric chronology of the early solar system. *Annu. Rev. Nucl. Sci.* 25:283–328
- Wetherill GW. 1980. Formation of the terrestrial planets. *Annu. Rev. Astron. Astrophys.* 18:77–113
- Wetherill GW. 1986. Accumulation of the terrestrial planets and implications concerning lunar origin. In *Origin of the Moon*, ed. WK Hartman, RJ Phillips, GJ Taylor, pp. 519–50. Houston: Lunar Planet. Inst.
- Wetherill GW. 1991. Why isn't Mars as big as Earth? *Proc. Lunar Planet. Sci. Conf., 22nd, Houston, March 18–22*, pp. 1495–96. Houston: Lunar Planet. Inst.
- Wetherill GW, Stewart GR. 1989. Accumulation of a swarm of small planetesimals. *Icarus* 77:330–57
- Wetherill GW, Stewart GR. 1993. Formation of planetary embryos: effects of fragmentation, low relative velocity, and independent variation of eccentricity and inclination. *Icarus* 106:190–209
- Whitney BA, Wood K, Bjorkman JE, Wolff MJ. 2003. Two-dimensional radiative transfer in protostellar envelopes: I. Effects of geometry on class I sources. *Astrophys. J.* 591:1049–63
- Williams J. 2010. Telescopes versus microscopes: the puzzle of iron-60. *EAS Publ. Ser.* 41:233–52
- Yin Q-Z, Jacobsen SB, Yamashita K, Blichert-Toft J, Telouk P, Albarede F. 2002. A short timescale for terrestrial planet formation from Hf-W chronometry of meteorites. *Nature* 418:949–52
- Yin Q-Z, Tollstrup D, Wimpenny J. 2010. Constraining the timing of the giant impact and the origin of the Earth-Moon system. *Proc. Int. Symp. Lunar Sci., Macau, March 25–26*, pp. 71–91. Macau: Macau Univ. Sci. Technol.
- Yurimoto H, Wasson JT. 2002. Extremely rapid cooling of a carbonaceous-chondrite chondrule containing very  $^{16}\text{O}$ -rich olivine and a  $^{26}\text{Mg}$ -excess. *Geochim. Cosmochim. Acta* 66:4355–63
- Zhang Y. 1998. The young age of Earth. *Geochim. Cosmochim. Acta* 18:3185–89
- Zsom A, Ormel CW, Güttler C, Blum J, Dullemond CP. 2010. The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? *Astron. Astrophys.* 513:A57



# Contents

Plate Tectonics, the Wilson Cycle, and Mantle Plumes: Geodynamics from the Top <i>Kevin Burke</i> .....	1
Early Silicate Earth Differentiation <i>Guillaume Caro</i> .....	31
Building and Destroying Continental Mantle <i>Cin-Ty A. Lee, Peter Luffi, and Emily J. Chin</i> .....	59
Deep Mantle Seismic Modeling and Imaging <i>Thorne Lay and Edward J. Garnero</i> .....	91
Using Time-of-Flight Secondary Ion Mass Spectrometry to Study Biomarkers <i>Volker Thiel and Peter Sjövall</i> .....	125
Hydrogeology and Mechanics of Subduction Zone Forearcs: Fluid Flow and Pore Pressure <i>Demian M. Saffer and Harold J. Tobin</i> .....	157
Soft Tissue Preservation in Terrestrial Mesozoic Vertebrates <i>Mary Higby Schweitzer</i> .....	187
The Multiple Origins of Complex Multicellularity <i>Andrew H. Knoll</i> .....	217
Paleoecologic Megatrends in Marine Metazoa <i>Andrew M. Bush and Richard K. Bambach</i> .....	241
Slow Earthquakes and Nonvolcanic Tremor <i>Gregory C. Beroza and Satoshi Ide</i> .....	271
Archean Microbial Mat Communities <i>Michael M. Tice, Daniel C.O. Thornton, Michael C. Pope, Thomas D. Olszewski, and Jian Gong</i> .....	297
Uranium Series Accessory Crystal Dating of Magmatic Processes <i>Axel K. Schmitt</i> .....	321

A Perspective from Extinct Radionuclides on a Young Stellar Object: The Sun and Its Accretion Disk <i>Nicolas Dauphas and Marc Chaussidon</i> .....	351
Learning to Read the Chemistry of Regolith to Understand the Critical Zone <i>Susan L. Brantley and Marina Lebedeva</i> .....	387
Climate of the Neoproterozoic <i>R.T. Pierrehumbert, D.S. Abbot, A. Voigt, and D. Koll</i> .....	417
Optically Stimulated Luminescence Dating of Sediments over the Past 200,000 Years <i>Edward J. Rhodes</i> .....	461
The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future <i>Francesca A. McInerney and Scott L. Wing</i> .....	489
Evolution of Grasses and Grassland Ecosystems <i>Caroline A.E. Strömberg</i> .....	517
Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO <sub>2</sub> Capture and Storage <i>Peter B. Kelemen, Juerg Matter, Elisabeth E. Streit, John F. Rudge, William B. Curry, and Jerzy Blusztajn</i> .....	545
Ice Age Earth Rotation <i>Jerry X. Mitrovica and John Wahr</i> .....	577
Biogeochemistry of Microbial Coal-Bed Methane <i>Dariusz Strapoć, Maria Mastalerz, Katherine Dawson, Jennifer Macalady, Amy V. Callaghan, Boris Wawrik, Courtney Turich, and Matthew Ashby</i> .....	617
<b>Indexes</b>	
Cumulative Index of Contributing Authors, Volumes 29–39 .....	657
Cumulative Index of Chapter Titles, Volumes 29–39 .....	661

## Errata

An online log of corrections to *Annual Review of Earth and Planetary Sciences* articles may be found at <http://earth.annualreviews.org>