Timescales of the Solar Protoplanetary Disk

Sara S. Russell
The Natural History Museum

Lee Hartmann
Harvard-Smithsonian Center for Astrophysics

Jeff Cuzzi
NASA Ames Research Center

Alexander N. Krot
Hawai'i Institute of Geophysics and Planetology

Matthieu Gounelle
CSNSM–Université Paris XI

Stu Weidenschilling
Planetary Science Institute

We summarize geochemical, astronomical, and theoretical constraints on the lifetime of the protoplanetary disk. Absolute Pb-Pb-isotopic dating of CAIs in CV chondrites (4567.2 ± 0.7 m.y.) and chondrules in CV (4566.7 ± 1 m.y.), CR (4564.7 ± 0.6 m.y.), and CB (4562.7 ± 0.5 m.y.) chondrites, and relative Al-Mg chronology of CAIs and chondrules in primitive chondrites, suggest that high-temperature nebular processes, such as CAI and chondrule formation, lasted for about 3–5 m.y. Astronomical observations of the disks of low-mass, pre-main-sequence stars suggest that disk lifetimes are about 3–5 m.y.; there are only few young stellar objects that survive with strong dust emission and gas accretion to ages of 10 m.y. These constraints are generally consistent with dynamical modeling of solid particles in the protoplanetary disk, if rapid accretion of solids into bodies large enough to resist orbital decay and turbulent diffusion are taken into account.

1. INTRODUCTION

Both geochemical and astronomical techniques can be applied to constrain the age of the solar system and the chronology of early solar system processes (e.g., *Podosek and Cassen,* 1994). We can study solid material that is believed to date from that time, and that is now preserved in minor bodies in the solar system (asteroids and comets); we can observe circumstellar disks around young solar-mass stars that are similar to the young Sun by measuring the emission of dust around them at appropriate wavelengths (infrared and millimeter), and we can make theoretical models of how disk material is likely to behave. In this chapter, we will address and review the current state of knowledge of these three strands of evidence.

A necessary first stage is to define what we mean by the accretion disk lifetime. We assume that the process of planet formation in the solar system was multistage. First, solids evolved in the protoplanetary disk. These solids began as interstellar and circumstellar grains, mostly *amorphous* material less than 1 µm in size. The constituents of chondritic meteorites — chondrules, refractory inclusions [Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)], Fe,Ni-metal grains, and fine-grained matrices — are largely *crystalline*, and were formed from thermal processing of these grains and from condensation of solids from gas. Calcium-aluminum-rich inclusions are tens of micrometers to centimeter-sized irregularly shaped or rounded objects composed mostly of oxides and silicates of Ca, Al, Ti, and Mg, such as corundum (Al_2O_3), hibonite ($CaAl_{12}O_{19}$), grossite ($CaAl_4O_7$), perovskite ($CaTiO_3$), spinel ($MgAl_2O_4$), Al,Ti-pyroxene (solid solution of $CaTi^{4+}Al_2O_6$, $CaTi^{3+}AlSiO_6$, $CaAl_2SiO_6$, and $CaMgSi_2O_6$), melilite (solid solution of $Ca_2MgSi_2O_7$ and $Ca_2Al_2SiO_7$), and anorthite ($CaAl_2Si_2O_8$). Ameboid olivine aggregates are physical aggregates of individual condensate particles: forsterite (Mg_2SiO_4), Fe,Ni-metal, and CAIs composed of spinel, anorthite, and Al,Ti-pyroxene. Evaporation and condensation appear to have been the dominant processes during formation of refractory inclusions. Subsequently, some CAIs experienced melting to various degrees and crystallization over timescales of days under highly reducing (solar nebula) conditions. Chondrules are igneous, rounded objects, 0.01–10 mm in size, composed largely of ferromagnesian olivine ($Mg_{2-x}Fe_xSiO_4$) and pyroxene ($Mg_{1-x}Fe_xSiO_3$, where $1 < x < 0$), Fe,Ni-metal, and glassy or microcrystalline mesostasis. Multiple episodes of melting of preexisting solids accompanied by evaporation-recondensation are believed to have been the dominant processes during chondrule formation. Chondrules appear to have formed in more oxidizing environments than CAIs, and cooled more quickly.

It is widely believed that from these building blocks, asteroids were ultimately formed, and subsequently experienced parent-body processes, such as aqueous alteration and thermal metamorphism. Larger bodies capable of retaining heat, and/or bodies rich in radioactive nuclides, may have, in addition, experienced melting and differentiation. Shock processing, by impact within the asteroid belt, may also have occurred throughout asteroidal history. These processes are often assumed to have occurred sequentially, although this is almost certainly an oversimplification. For example, ^{53}Mn and ^{129}I evidence suggest that aqueous alteration of chondrites lasted over >20 m.y. (*Endreß et al.,* 1996; *Krot et al.,* 2006), longer than the time taken for some small asteroids to differentiate (*Wadhwa and Lugmair,* 1996; *Lugmair and Shukolyukov,* 1998). However, *Hoppe et al.* (2004) suggested that aqueous activity on the Orgueil chondrite parent asteroid lasted <10 m.y. Iodine-129 data further suggest that chondrule formation overlapped with the formation of the first melted planetesimals (*Gilmour et al.,* 2000). From a cosmochemical point of view (sections 2–4), we can assume that the disk "begins" at the time that the first solids are processed, and "ends" at the time at which asteroidal accretion stops. The time of asteroidal accretion can be constrained by dating early processes that must have occurred in an asteroidal environment. From an observational point of view, we assume that the disk lifetime dates from the point at which the star first forms, to the point at which the dust around it disappears, presumably because it has accreted into planetesimals or planets. Theoretical modeling can assist in determining how long dust grains can realistically remain within a solar accretion disk environment.

2. ABSOLUTE AGES OF PROTOPLANETARY DISK MATERIALS DEFINED BY LONG-LIVED RADIONUCLIDES

2.1. Introduction

Many radioactive isotopes can be used as geologic clocks. Each isotope decays at a fixed rate. Once this decay rate is known, the length of time over which decay has been occurring can be estimated by measuring the amount of remaining radioactive parent compared to the amount of stable daughter isotopes. Older objects will have built up a higher fraction of daughter isotopes than younger ones with the same parent/daughter element ratios. For all radioactive decay schemes, the clock "starts" at the time at which the object cools below a temperature (the "closure temperature") at which the parent and daughter isotopes become essentially immobile; this temperature depends on the decay scheme that is used, and on the minerals in which they are trapped. The age is then given by

$$t = 1\frac{1}{\lambda}\ln\left(1 + \frac{D}{P}\right)$$

where t = age, D = abundance of the daughter isotope, and P = abundance of the parent isotope. The ratio D/P can most easily be measured by constructing an isochron. An example is for the Rb-Sr system, where Rb decays to Sr with a half-life of 4.88×10^{10} yr. From a single rock, coexisting minerals with varying Rb/Sr ratios are measured both for Sr isotopes and $^{87}Rb/^{86}Sr$. A plot of $^{87}Rb/^{86}Sr$ as a function of $^{87}Sr/^{86}Sr$ will form a correlation (the isochron) that has a slope defining $^{87}Sr/^{87}Rb$ that can be plugged into the equation above to yield age information. The intercept of the isochron indicates whether the system has experienced late-stage disturbance; this will reequilibrate the Sr isotopes and cause the intercept to fall at higher $^{87}Sr/^{86}Sr$.

Radioactive isotopes with a half-life on the order of the age of the solar system are the most accurate ones to be used to gain absolute age dates of early solar system material. The most common long-lived dating systems used in meteoritics are Pb-Pb, Rb-Sr, and K-Ar [and its sister technique Ar-Ar (e.g., *Turner,* 1970)]. The practical aspects of the use of these systems are described in detail by *Tilton* (1988a). In this chapter, we will focus on results from the Pb-Pb system, which has given the most precise age-dating information for the very oldest meteoritic objects, especially for those that are refractory and thus have a high initial ratio of U to volatile Pb.

The major assumptions made in calculating the ages are that (1) the initial isotopic composition of the radiogenic element is known, or can be accurately calculated from the acquired data, or it was initially so rare in the mineral being measured that it can be ignored; (2) no resetting of the isotopic clock was made, by gain or loss of the parent or daughter isotopes since "isotopic closure," i.e., since the initial cooling of the rock; (3) the half-lives of the isotopes are accurately known; and (4) the initial isotopic composition of the parent element is known to sufficient accuracy. The most accurate results can be obtained for samples that have a high natural initial ratio of parent/daughter element, since in these samples the isotopic ratio of the daughter element is most affected by the addition of a radiogenic component.

The Pb-Pb system utilizes two different decay schemes: the decay of ^{235}U to ^{207}Pb, and ^{238}U to ^{206}Pb, both via several intermediary decay products. Measurements of ^{206}Pb and ^{207}Pb, normalized to nonradiogenic ^{204}Pb, are correlated (therefore producing an "isochron"), which yields age information (Fig. 1a). Modern studies acquire more accurate results by normalizing to ^{206}Pb (Fig. 1b). This dating system

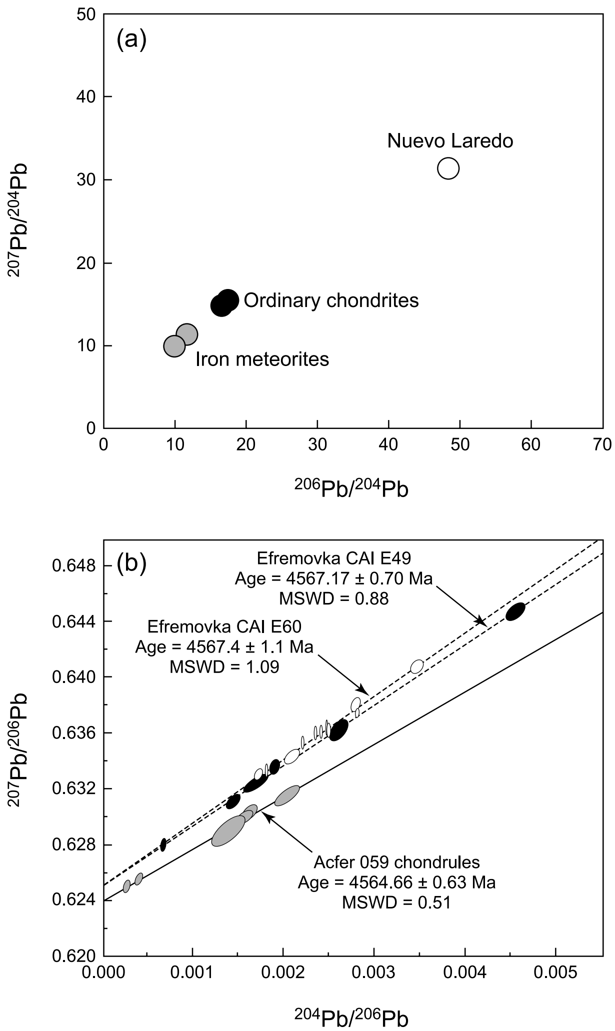

Fig. 1. **(a)** The first Pb-Pb isochron for meteorites. The isochron is composed from data from the ordinary chondrites Forest City (H5) and Modoc (L5), the iron meteorites Henbury and Canyon Diablo, and the eucrite Nuevo Laredo. Using modern assumptions about decay constants and initial Pb-isotopic composition, the slope of the line indicates an age of 4.50 ± 0.07 G.y. (see text). Data from *Patterson* (1956). **(b)** Pb-Pb isochrons for the six most radiogenic Pb-isotopic analyses of acid-washed chondrules from the CR chondrite Acfer 059 (solid line), and for acid-washed fractions from the Efremovka CAIs (dashed lines). ^{207}Pb/^{206}Pb ratios are not corrected for initial common Pb. Error ellipses are 2σ. Isochron age errors are 95% confidence intervals. From *Amelin et al.* (2002).

requires only measurement of the isotopic ratios of one element: Pb. No element/element ratios are required, which can be a major source of error in other dating systems, thus the data are potentially very accurate. However, Pb is mobile under many geological conditions, and so the possibility of post-crystallization redistribution must be carefully considered. For more details of the Pb-Pb dating technique, see, e.g., *Faure* (1986), *Henderson* (1982), and *Tilton* (1988a).

2.2. History of Attempts to Learn the Age of the Solar System

Early attempts to uncover the age of Earth utilized several ingenious, although inaccurate, techniques (e.g., *Darwin,* 1859; *Thomson,* 1897; *Holmes,* 1946). Estimates obtained using these techniques were in gross disagreement with each other.

A major breakthrough was provided by the discovery of radioactivity by *Becquerel* (1896a,b). Less than 10 years later, *Rutherford and Boltwood* (1905) realized the potential of radioactive decay as a tool to measure the age of Earth. The first accurate age dates of meteorites, and hence Earth, were published by Clair C. Patterson (*Patterson et al.,* 1955; *Patterson,* 1956). *Patterson et al.* (1955) recorded a Pb-Pb age of 4.57 ± 0.07 G.y. using an isochron composed of data for the eucrite Nuevo Laredo, the ordinary chondrites Forest City (H5) and Modoc (L5), and the iron meteorites Canyon Diablo (IIIAB) and Henbury (IIIAB) (Fig. 1a). Using more accurate values for the initial Pb composition and decay constants, the age was reduced to 4.50 ± 0.07 G.y. (*Tilton,* 1988b). The known age of the solar system has essentially not changed, within error, since this time.

2.3. Petrological Considerations

Calcium-aluminum-rich inclusions, composed of refractory minerals, have long been considered to represent the first solid condensates in the solar system (e.g., *Grossman,* 1972). The occasional presence of relict CAIs within Al-rich and in a few ferromagnesian chondrules (Figs. 2a–c) suggest that most CAIs probably formed earlier than most chondrules (*Krot and Keil,* 2002; *Krot et al.,* 2002, 2004). A single recent observation of a pyroxene-rich chondrule fragment apparently embedded in a CAI suggests that the formation of chondrules and CAIs may have overlapped in time and space (*Itoh and Yurimoto,* 2003). However, to date there is no quantitative chronological information available for this unique object. Recently, *Krot et al.* (2005a) described two additional igneous, anorthite-rich (Type C) CAIs containing relict chondrule fragments in the Allende meteorite. These authors concluded, however, that the chondrule-bearing Type C CAIs experienced late-stage remelting (~2 m.y. after formation of the CAIs with a canonical ^{26}Al/^{27}Al ratio of 5×10^{-5}) with addition of chondrule material in the chondrule-forming region. This interpretation is consistent with an age difference between the formation of CAIs and chondrules.

2.4. Absolute Ages of Calcium-Aluminum-rich Inclusions

Calcium-aluminum-rich inclusions yield the oldest reliably measured age dates of any solar system solid. Calcium-aluminum-rich inclusions typically have a high ratio of refractory U to volatile Pb, and thus are good targets for age

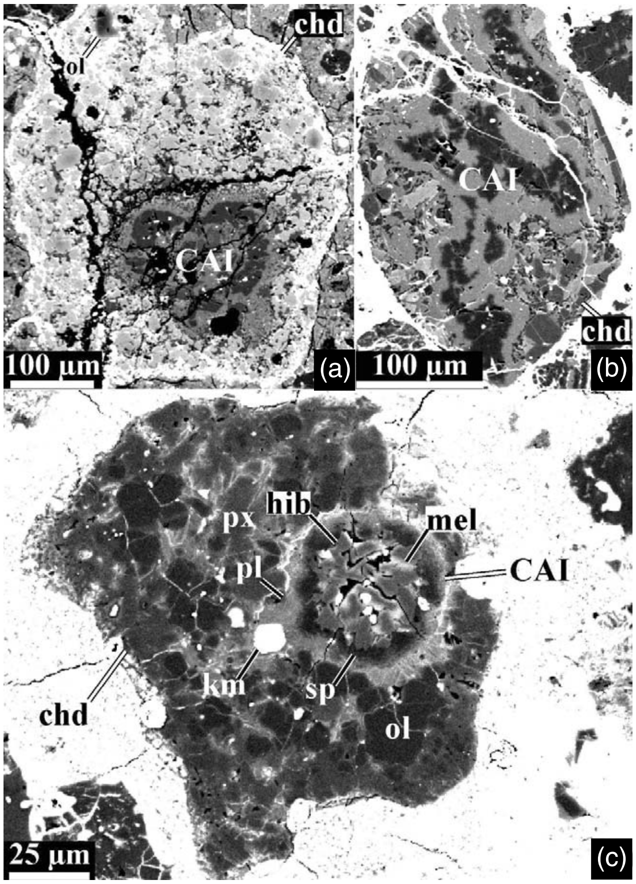

Fig. 2. Backscattered electron images of the CAI-bearing chondrules [**(a)**–**(c)**] and a chondrule-bearing CAI **(d)** in the ungrouped carbonaceous chondrites Acfer 094 **(a)** and Adelaide **(c)**, CH carbonaceous chondrite Acfer 182 **(b)**. **(a)** Relict CAI composed of hibonite and spinel is enclosed by a ferrous olivine chondrule. **(b)** Relict CAI consisting of spinel and anorthite is surrounded by an Al-rich chondrule composed of low-Ca pyroxene, high-Ca pyroxene, and fine-grained mesostasis. **(c)** Relict CAI composed of hibonite, perovskite, melilite, and spinel is enclosed by a magnesian chondrule consisting of olivine, low-Ca pyroxene, glassy mesostasis, and metal. aug = augite; en = enstatite; hib = hibonite; km = kamacite; mel = melilite; ol = forsteritic olivine; pg = pigeonite; sp = spinel; pv = perovskite; tr = troilite. From *Krot et al.* (2004).

dating using the Pb-Pb system. Early studies of chondrite ages typically included CAIs, chondrules, and matrix. *Tatsumoto et al.* (1976) studied several chondrules and refractory inclusions from the Allende meteorite. They reported that both chondrules and CAIs fall on a single isochron line, yielding an age of 4554 ± 4 m.y. A study by *Chen and Tilton* (1976) reported a significantly older age for Allende constituents of 4565 ± 4 m.y. Again, the ages of chondrules and CAIs were found to be indistinguishable from each other within analytical error. Matrix analyses reported during the same study (*Chen and Tilton,* 1976) yielded age dates several million years younger than the chondrules and CAIs, probably reflecting more prolonged and extensive asteroidal alteration of the matrix. Later studies focused on measuring mineral separates from CAIs alone. *Chen and Wasserburg* (1981) made the first measurement of this type, with samples of several Type B CAIs giving an age of 4559 ± 4 m.y.

Recognizing that post-formational redistribution of Pb from matrix to CAIs was a potential problem for measuring Pb-Pb ages of Allende inclusions, *Manhès et al.* (1988) [summarized in English by *Allègre et al.* (1995)] attempted a new approach. They analyzed several CAIs using "differential dissolution." This is a procedure that dissolves the CAIs in stages, using progressively more aggressive reagents. The model ages obtained for the CAIs from the progressive dissolution fractions increased, suggesting that Pb from the matrix was contaminating the early dissolution steps. The ages they obtained range between 4565 ± 1 m.y. and 4568 ± 3 m.y., and they interpreted the latter value as representing the true age of Allende CAIs; no significant age difference was found between different CAIs.

One way around the problem of Pb redistribution after asteroidal accretion is to study meteorites that have experienced much less alteration than Allende. Precise Pb-Pb ages were reported for two CAIs from the reduced CV3 chondrite Efremovka (*Amelin et al.,* 2002). A Type B inclusion yielded an age of 4567.4 ± 1.1 m.y., and a compact Type A inclusion yielded an age of 4567.2 ± 0.7 m.y. These values are within error of the age of Allende inclusions determined by *Manhès et al.* (1988). However, these measurements are model ages, and make the assumption that a single age can be obtained for CAIs, i.e., that they experienced no processing after this formation event. Only by analyzing several separates from one igneous object can the effects of later disturbance be accounted for. Because CAIs have high U/Pb ratios, the Pb isotopes are particularly susceptible to disturbance due to postformation heating events. Clearly, additional analyses, preferably of careful mineral separates of single large CAIs, need to be made.

Perovskite grains in CAIs are present as phenocrysts and are clearly among the first crystals to form within the CAI, thus there is a possibility that they may be relict. Lead-isotopic measurements of individual perovskite grains in the Allende (CV3) and Murchison (CM2) CAIs yielded ages of 4565 ± 34 m.y. and 4569 ± 26 m.y. respectively (*Ireland et al.,* 1990). Thus, there is no evidence at the moment to suggest that any grains within a CAI are relicts that significantly predated the rest of the inclusion.

Calcium-aluminum-rich inclusions have been age dated using the Rb-Sr system (e.g., *Podosek et al.,* 1991). Rubidium-87 has a half-life of 4.88×10^{10} yr and decays to ^{87}Sr. These measurements have yielded age dates in line with those for Pb-Pb dating (~4.56 G.y.). Exact age dates are often difficult to obtain because typical CAI measurements indicate a period of Sr remobilization at younger ages. The very old nature of CAIs is also indicated by the observation that the isochron intercept for the Rb-Sr system falls at very low $^{87}Sr/^{86}Sr$ values. The intercept value for Allende CAIs, coined "ALL" by *Gray et al.* (1973), provides the lowest $^{87}Sr/^{86}Sr$ of any solar system material.

2.5. Absolute Ages of Chondrules

The absolute age of chondrules has proved difficult to measure because they typically have lower U/Pb ratios than CAIs, and are typically smaller than the largest CAIs (at least in CV3 chondrites). In one of the first studies of the Allende CV3 meteorite, *Fireman* (1970) reported a K/Ar age of ~4.44 G.y. for a single large chondrule. Other scientists working in the 1970s (*Chen and Tilton,* 1976; *Tatsumoto et al.,* 1976) (see section 2.2 above) found that Allende chondrules are indistinguishable in Pb-Pb age to Allende CAIs within analytical errors (typically ~4 m.y.). *Tera et al.* (1996) pointed out that many Pb-Pb measurements of chondrules are contaminated by terrestrial Pb. More precise age dates have only recently been reported by Amelin and coworkers (*Amelin et al.,* 2002, 2004), but so far only whole chondrules, not mineral separates, have been possible to measure; thus isochrons from individual objects have not yet been obtained. An isochron for a population of Allende chondrules yields an age of 4566.7 ± 1.0 m.y., indistinguishable from the ages of Efremovka CAIs (*Amelin et al.,* 2004). An isochron plotting four whole chondrules from the CR chondrite Acfer 059 yielded an age of 4564.7 ± 0.6 m.y., 2.5 ± 1.2 m.y. younger than the mineral separates from CAIs measured in the Efremovka CV meteorite by the same technique (*Amelin et al.,* 2002). These authors noted that the low error on the isochron regression line suggests that the chondrules analyzed had a similar age to each other, probably all forming within ~1.2 m.y. *Amelin and Krot* (2005) have recently reported absolute ages of chondrule-like silicate clasts from the CB meteorites Gujba (4562.7 ± 0.5 m.y.) and Hammadah al Hamra 237 (4562.8 ± 0.9 m.y.). We would like to emphasize that the origin of the chondrule-like clasts in CB chondrites is controversial, with both nebular (*Weisberg et al.,* 2001; *Campbell et al.,* 2002) and asteroidal (*Rubin et al.,* 2003) models proposed. It is not, therefore, clear whether they can be considered chondrules in the usually understood sense of the word. For example, *Amelin and Krot* (2005) and *Krot et al.* (2005b) concluded that chondrules in CB chondrites formed during a giant impact between Moon-sized planetary embryos after the protoplanetary disk largely (but not completely) dissipated. As a result, the significance of the CB "chondrule" absolute ages for constraining the lifetime of the solar nebula remains unclear.

In summary, Pb-Pb ages currently provide the most precise ages of early solar system solids. The span of ages represented by Pb-Pb dates of chondritic objects is several million years, with CV CAIs and chondrules apparently the oldest, and objects from CB meteorites around 4–5 m.y. younger. If we assume that objects formed in a nebular setting prior to the final accretion of the asteroidal parent bodies and dissipation of the disk, then this constrains a minimum age for the solar accretion disk.

3. RELATIVE AGES OF PROTOPLANETARY DISK MATERIALS DEFINED BY SHORT-LIVED RADIONUCLIDES

3.1. Introduction

Isotopes with half-lives that are very much shorter than the age of the solar system (<100 m.y.) may once have been present in solar system material, but are now considered extinct. However, their initial presence in some early solar system materials can be detected by an excess of their daughter isotope. Evidence for the existence of several short-lived isotopes has now been found in meteorites; these are summarized in Table 1. In principle, short-lived isotopes can provide relative ages of old components with very high precision.

The initial abundance of the short-lived isotope can be quantified if there are regions of variable parent/daughter elemental ratios within a single object that formed during one event (e.g., different minerals within an igneous object, or between several objects that are assumed to be the same age). Figure 3a shows an example of evidence for the extinct short-lived isotope ^{26}Al within an igneous (Type B) CAI. A correlation ("isochron") is observed between $^{27}Al/^{24}Mg$ and $^{26}Mg/^{24}Mg$. Minerals with lower Al/Mg ratios, such as spinels, contain a lower $^{26}Mg/^{24}Mg$ ratio than minerals with high Al/Mg ratios such as anorthite. This is because the effect of ^{26}Al decay on the Mg-isotopic composition is most significant for the minerals with high Al/Mg ratios. Since the excess in ^{26}Mg is due to the decay of ^{26}Al, the slope of the isochron is equal to the initial $^{26}Al/^{27}Al$ ratio. If several objects formed at different times from an isotopically similar reservoir, then the older objects will yield a

TABLE 1. Short-lived isotopes initially present in meteorites.

Radioactive Isotope (R)	T (m.y.)	Daughter Isotope	Stable Isotope (S)	Initial Abundance (R/S)
^{7}Be	52 d	^{7}Li	^{9}Be	6×10^{-3}
^{41}Ca	0.1	^{41}K	^{40}Ca	1.5×10^{-8}
^{36}Cl	0.3	^{36}S	^{35}Cl	$> 1.1 \times 10^{-5}$
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5}
^{10}Be	1.5	^{10}B	^{9}Be	$4–14 \times 10^{-3}$
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$0.1–1.6 \times 10^{-6}$
^{53}Mn	3.7	^{53}Cr	^{55}Mn	$1–12 \times 10^{-5}$
^{107}Pd	6.5	^{107}Ag	^{108}Pd	$>4.5 \times 10^{-5}$
^{182}Hf	9	^{182}W	^{180}Hf	$>1.0 \times 10^{-4}$
^{129}I	16	^{129}Xe	^{127}I	1.0×10^{-4}
^{92}Nb	36	^{92}Zr	^{93}Nb	$10^{-5} – 10^{-3}$
^{244}Pu	81	Fission products	^{238}U	$4–7 \times 10^{-3}$
^{146}Sm	103	^{142}Nd	^{144}Sm	7×10^{-3}

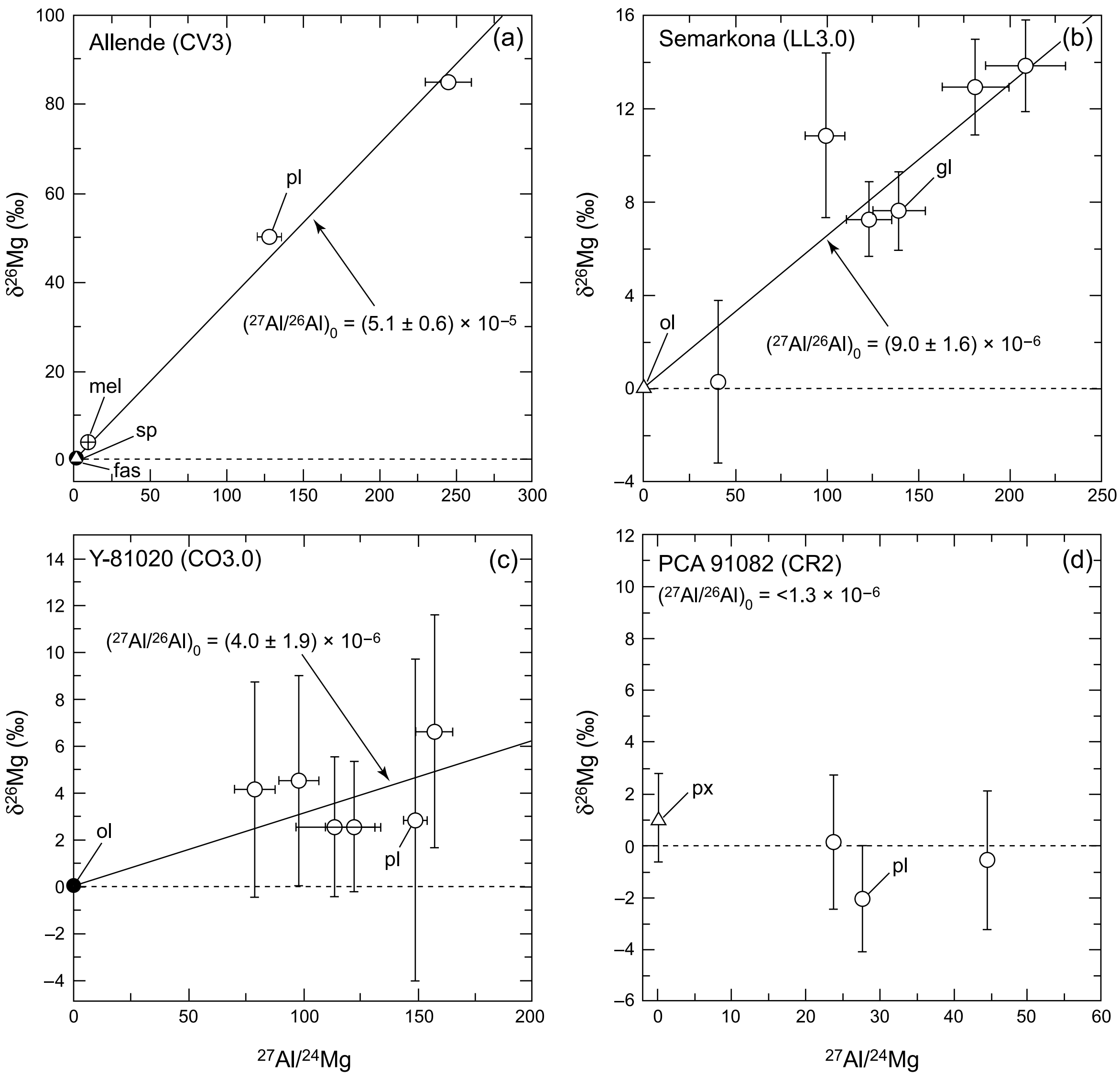

Fig. 3. Al-Mg evolutionary diagram for **(a)** an igneous (Type B) CAI from the CV3 chondrite Allende (from *Lee et al.,* 1976), **(b)** a ferromagnesian chondrule from the LL3.0 chondrite Semarkona (from *Kita et al.,* 2000), **(c)** a ferromagnesian chondrule from the CO3.0 chondrite Y-81020 (from *Kunihiro et al.,* 2004), and **(d)** an Al-rich chondrule from the CR2 chondrite PCA 91082 (from *Hutcheon et al.,* 2004). The observed range in the initial ^{26}Al/^{27}Al ratios, if interpreted chronologically, suggests that chondrule formation lasted for at least 2–3 m.y. after CAI formation. fas = fassaite; gl = glass; ol = olivine; pl = plagioclase; px = pyroxene; sp = spinel.

higher initial ^{26}Al/^{27}Al ratio than the younger ones (i.e. produce an isochron with a steeper slope), thus age information can be extracted, as the half-life of ^{26}Al is known. The intercept ^{26}Mg/^{24}Mg indicates the initial ^{26}Mg/^{24}Mg of the rock, and can indicate whether resetting of the isotope clock has taken place. If the system is equilibrated with respect to Mg isotopes after some component of ^{26}Al has decayed, then this caused the bulk ^{26}Mg/^{24}Mg of the system to be raised, i.e., the intercept to increase (e.g., *Podosek et al.,* 1991). The initial abundance of other short-lived isotopes is calculated in a similar way. For reviews of the use of short-lived isotopes as chronometers, see, for example, *Swindle et al.* (1996), *Gilmour and Saxton* (2001), and *McKeegan and Davis* (2003).

The use of short-lived isotopes as chronometers involves making several assumptions. The main assumptions are that (1) all the components used to make an isochron formed from a reservoir that was initially isotopically homogeneous with respect to the radioactive parent of the short-lived isotope, (2) the components measured are coeval and initially had the same daughter isotopic composition, (3) no post-formational redistribution occurred, and (4) the half-lives are accurately known. Post-formational redistribution of isotopes, and the relationship between analyzed phases, can to some extent be monitored by geochemical and mineralogical studies. For example, isotope redistribution may have occurred in objects for which there is mineralogical evidence for secondary mobilization by metamorphism or aqueous processing. The assumption of homogeneity is considered in detail in the next section.

3.2. Initial Abundances and Distribution

The initial abundances, as far as we know them, of the known short-lived isotopes in the early solar system are summarized in Table 1. The initial values for ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn, and ^{129}I are taken from values measured in CAIs, which are known to be extremely ancient solids (see section 2 above). Values for the other known short-lived isotopes are taken from other chondritic components, achondrites, and iron meteorites. The parent elements of these isotopes are not refractory enough to have initially been present at a sufficiently high level in CAIs. In this review, we will focus on the isotopes ^{26}Al and ^{53}Mn. This is because these isotopes have been measured in a wide range of components (chondrules and CAIs) assumed to have formed prior to asteroidal accretion, and thus they can potentially provide the most information about early solar system chronology. The short-lived isotope ^{129}I has also been measured in a wide range of samples, including individual chondritic components (e.g., *Whitby et al.,* 2004). Some of these measurements are of primary age dates (e.g., *Gilmour et al.,* 2000; *Whitby et al.,* 2002), but the use of I-Xe as a chronometer of primary mineral crystallization is hampered by the extreme mobility of both I and radiogenic Xe under many geological conditions.

Both the formation mechanism of these nuclides and their distribution mechanism are currently debated. The short-lived isotopes must have been formed soon before the formation of the first solar system solids, because they were still "live" — i.e., present in measurable quantities — when these solids formed. Mechanisms for the formation of these isotopes are that they all formed in a star, or in the local solar environment. A stellar source for short-lived isotopes could have been a supernova, a Wolf-Rayet star, or, less likely, because they are not associated with star-formation regions, a thermally pulsing asymptotic giant branch (AGB) star, and they were then injected into the solar system (e.g., *Arnould et al.,* 1997; *Cameron et al.,* 1995; *Goswami and Vanhala,* 2000; *Boss and Vanhala,* 2001; *Busso et al.,* 2003). If an external stellar source for the short-lived isotopes is assumed, then the existence of ^{10}Be is at first glance problematic, as this isotope is not formed in stellar environments (*McKeegan et al.,* 2000). However, *Desch et al.* (2004) presented a model in which 80% of the ^{10}Be inferred to have been present in CAIs is a trapped galactic cosmic ray (GCR) component, and the remainder formed from spallation reactions by GCRs.

Alternatively, all, or a component of, the isotopes ^{10}Be, ^{26}Al, ^{41}Ca, and ^{53}Mn may have formed by irradiation, i.e., spallation mainly due to energetic protons and ^{3}He nuclei, in the early solar system itself, close to the young Sun (*Lee et al.,* 1998; *Gounelle et al.,* 2001; *Goswami et al.,* 2001; *Leya et al.,* 2003; *Chaussidon and Gounelle,* 2006), and could then have been distributed to asteroidal distances in the protoplanetary disk via an outflow, for example, in CAIs and chondrules within an X-wind (*Shu et al.,* 1996, 2001).

The irradiation model fails to produce the extinct isotope ^{60}Fe. An upper limit for the initial presence of ^{60}Fe in CAIs is at levels of $(^{60}Fe/^{56}Fe)_0 = 1.6 \times 10^{-6}$ (*Birck and Lugmair,* 1988). Recent measurements of its decay product, ^{60}Ni, have been reported in chondritic sulphides from Bishunpur (LL3.1), demonstrating it was initially present in these minerals at levels of $^{60}Fe/^{56}Fe = \sim 1 \times 10^{-7}$ (*Tachibana and Huss,* 2003; *Guan et al.,* 2003). Silicate chondrules appararently formed in an environment in which the $^{60}Fe/^{56}Fe$ was $2–5 \times 10^{-7}$ (*Tachibana et al.,* 2005). Sulfides in Semarkona (LL3.0) contained ^{60}Fe at levels that are even higher — $(^{60}Fe/^{56}Fe)_0 = (1.00 \pm 0.15) \times 10^{-6}$ — although the Fe-Ni system may have experienced remobilization in these samples (*Moustefoui et al.,* 2003, 2004). This is the expected level for late-formed constituents of a long-lasting solar nebula initially seeded by supernova material (*Tachibana et al.,* 2003), and above expected normal galactic background levels. While the proportions of the isotopes formed by each mechanism is unknown, it is probable that the roster of short-lived isotopes as a whole formed by more than one mechanism (e.g., *Russell et al.,* 2001; *Huss et al.,* 2001). The formation of short-lived isotopes is discussed in more detail in *Chaussidon and Gounelle* (2006).

The formation and distribution mechanism of the short-lived isotopes will define the likelihood of whether the initial abundances of short-lived isotopes recorded in CAIs represent values that were once homogeneously present in the solar system as a whole. It is highly improbable that the isotopes that formed by irradiation close to the Sun would be initially homogeneously distributed in all chondritic components, as this would require all components to have been subjected to the same initial irradiation conditions onto the same starting composition and subsequent homogenization in the solar nebula. If these isotopes formed by production in a star, then they may or may not have been homogeneously mixed into the solar accretion disk (*Vanhala,* 2001; *Boss and Vanhala,* 2001; *Vanhala and Boss,* 2002; *Boss,* 2004).

Thus the use of short-lived isotopes as age-dating tools for early solar system objects is limited by the current lack of understanding of their initial distribution. Most authors make an assumption of homogeneity in order to tentatively draw chronological conclusions; this assumption was recently strengthened, at least on an asteroidal scale, by precise measurements of Mg isotopes in bulk chondrite groups (*Bizzarro et al.,* 2004). Below, we summarize the data acquired so far and discuss its implications and limitations for understanding solar system chronology.

3.3. Short-lived Isotope Abundance in Chondrules and Calcium-Aluminum-rich Inclusions

Quantitative information about the age difference between chondritic objects can be obtained from isotope measurements using short-lived isotopes.

3.3.1. Aluminum-26. From thousands of individual measurements by ion microprobe, it has emerged that isochrons determined from high Al/Mg minerals from most unaltered, typical CAIs are characterized by a canonical initial ratio $^{26}Al/^{27}Al = 4–5 \times 10^{-5}$ (*MacPherson et al.,* 1995; *Russell et al.,* 1996, 1998). High-precision ICP-MS analyses of unaltered CAIs suggest that the initial $^{26}Al/^{27}Al$ content of many CAIs may have been as high as 7×10^{-5} (e.g., *Galy et al.,* 2004; *Young et al.,* 2005). The study of *Young et al.* (2005) showed that a single CAI may contain some minerals with an initial $^{26}Al/^{27}Al$ ratio of $\sim 7 \times 10^{-5}$ igneously associated with minerals with initial $^{26}Al/^{27}Al$ of $\sim 5 \times 10^{-5}$, suggesting an extended high-temperature nebular history. We note, however, that the "supracanonical" $^{26}Al/^{27}Al$ ratio in the CV CAIs reported by *Young et al.* (2005) is not without controversy; e.g., some bulk Mg-isotopic measurements of Allende CAIs by ICP-MS revealed a lower model isochron of $(5.25 \pm 0.1) \times 10^{-5}$ (*Bizzarro et al.,* 2004).

A significant proportion of CAIs contain much less, or ummeasurably low, levels of initial ^{26}Al. These include the so-called FUN inclusions (*MacPherson et al.,* 1988), some Type C CAIs (*Wark,* 1987; *Hutcheon et al.,* 2004; *Krot et al.,* 2005a), grossite- and hibonite-rich CAIs in CH chondrites (*MacPherson et al.,* 1989; *Weber et al.,* 1995), and R chondrites (*Bischoff and Srinivasan,* 2003) and CAIs that have experienced extensive secondary elemental redistribution (*MacPherson et al.,* 1995). There are very little data for the related refractory inclusion type, AOAs, but the data that exists point to these having an initial $^{26}Al/^{27}Al$ ratio of around 3×10^{-5} (*Itoh et al.,* 2002).

In situ measurements of chondrules yield initial $^{26}Al/^{27}Al$ values clearly lower than the canonical CAI value, and in general, the values recorded are more variable than for the majority of CAIs. Chondrules from unmetamorphosed ordinary chondrites typically formed with $^{26}Al/^{27}Al \sim 1 \times 10^{-5}$ (e.g., *Russell et al.,* 1996; *Kita et al.,* 2000, *McKeegan et al.,* 2001; *Mostefaoui et al.,* 2002). Other chondrules, from higher metamorphic subgrades (>3.1) of ordinary chondrites, have lower initial values, which could be ascribed to metamorphic resetting (*Huss et al.,* 2001). In carbonaceous chondrites, there is evidence from unaltered CR and CV meteorites for a range in initial $^{26}Al/^{27}Al$ values in chondrules, ranging from 3×10^{-6} to 1×10^{-5} in samples for which evidence for initial ^{26}Al could be found (*Tachibana et al.,* 2003; *Hutcheon et al.,* 2004). *Kunihiro et al.* (2004) also suggested that the initial ^{26}Al abundance varied between chondrules from carbonaceous (initial $^{26}Al/^{27}Al \sim 4 \times 10^{-6}$) and ordinary chondrite groups (initial $^{26}Al/^{27}Al \sim 7 \times 10^{-6}$), suggesting differences in asteroidal accretion times between chondritic parent bodies. The difference in initial ^{26}Al abundance between different chondrules, and the much higher values observed in CAIs, could be interpreted as indicating that the period of formation of nebular solids, from CAIs to the youngest chondrules, extended over at least ~4 m.y. Alternatively, chondrules and CAIs could have formed in regions different to each other in Al-isotopic composition.

Recent bulk Mg-isotopic measurements of Allende chondrules yield a range of $(^{26}Al/^{27}Al)_I$ from $(5.66 \pm 0.80) \times 10^{-5}$ to $(1.36 \pm 0.52) \times 10^{-5}$ (*Bizzarro et al.,* 2004). However, because these measurements involve much lower amounts of $^{26}Mg^*$ compared to CAIs, the $(^{26}Al/^{27}Al)_I$ in chondrules is much more sensitive to fractionation laws and assumed initial Mg-isotopic composition, and so further work is required to explore these results and their implications.

More clear-cut chronological information can be obtained from single objects that have experienced more than one stage in their history. *Hsu et al.* (2000) reported a CAI with an inner zone once containing $^{26}Al/^{27}Al$ at the canonical level of $\sim 5 \times 10^{-5}$ and outer zone depleted in initial ^{26}Al; the authors interpreted this to indicate that the whole CAI initially contained $^{26}Al/^{27}Al$ at $\sim 5 \times 10^{-5}$ and had experienced nebular remelting after the decay of ^{26}Al, indicating a several-million-year preasteroidal accretionary history for this object. Even more compelling is the rare presence of relic CAIs with disturbed Al-Mg systematics found within chondrules (*Krot et al.,* 2004). These inclusions are mineralogically similar to CAIs that formed with canonical $^{26}Al/^{27}Al$, and the disturbance of the Al-Mg systematics in these objects implies that the ^{26}Al in the CAI decayed ≥2 m.y. prior to their incorporation in the chondrule-forming event.

Overall, the data for ^{26}Al suggest that the formation of CAIs and chondrules may have occurred over several million years, assuming it was homogeneously distributed. There is firm evidence for an extended, >2-m.y. nebular history for some individual objects.

3.3.2. Manganese-53. *Birck and Allègre* (1988) reported the first Mn-Cr-isotopic measurements of two Allende CAIs. They concluded that CAIs had formed with an average initial $^{53}Mn/^{55}Mn$ ratio of $(4.37 \pm 1.07) \times 10^{-5}$. *Nyquist et al.* (2001) inferred an initial $^{53}Mn/^{55}Mn$ of $(2.81 \pm 0.31) \times 10^{-5}$ for the Efremovka CAIs, whereas *Papanastassiou et al.* (2002) reported initial values ranging from 1.0×10^{-5} to 12.5×10^{-5} for the Allende CAIs. *Papanastassiou et al.* (2002) suggested that the measured span in the initial $^{53}Mn/^{55}Mn$ ratio in CAIs results from metamorphic redistribution of Mn. Accurate determination of Mn-Cr systematics in CAIs is complicated by the fact that Mn is too volatile to have been initially present in high abundance in CAIs. This problem is discussed by *Lugmair and Shukolyukov* (1998), who suggest using an initial $^{53}Mn/^{55}Mn$ value for CAIs of $\sim 1.4 \times 10^{-5}$, a value chosen to fit well with other isotope systems.

Data for chondrules are limited, but appear more consistent than for CAIs. *Nyquist et al.* (1994, 2001) reported Mn-Cr data on unequilibrated ordinary chondrite chondrules. They found that Chainpur and Bishunpur chondrules formed when $^{53}Mn/^{55}Mn$ was equal to $(0.94 \pm 0.17) \times 10^{-5}$ and $(0.95 \pm 0.13) \times 10^{-5}$ respectively.

These data, if interpreted chronologically, would imply a formation time difference of ~6 m.y. between Allende CAIs and ordinary chondrite chondrules if an average value for the initial CAI value is used, or ~12 m.y. if the highest (i.e., apparently the oldest) value for CAI initial $^{53}Mn/^{55}Mn$ is used. This timescale, using the highest initial $^{53}Mn/^{55}Mn$, is clearly at odds with the timescale inferred from ^{26}Al data.

However, if the initial $^{53}Mn/^{55}Mn$ estimate of ~1.4×10^{-5} is used (*Lugmair and Shukolyukov,* 1998), the time difference between the initial value and the chondrules is only ~2 m.y., similar to what is inferred from ^{26}Al.

3.4. Short-lived Isotopes in Achondrites

Timescales of achondrite solidification may give some clues as to planetesimal formation timescales and therefore the end of the disk lifetime (although the disk may not have terminally dissipated at the time of the first planetesimal formation; see section 6). A few occurrences of short-lived ^{26}Al within achondrites have been recorded, including within eucrites (e.g., *Srinivasan et al.,* 1999; *Nyquist et al.,* 2003a), angrites (e.g., *Nyquist et al.,* 2003b), and ureilites (*Kita et al.,* 2003); for details, see *Wadhwa et al.* (2006). For the eucrite Asuka 881394, which is thought to have been a very early-formed rock on the HED parent body [which is possibly the asteroid 4 Vesta (e.g., *Consolmagno and Drake,* 1977)], Mn-Cr-isotopic analyses determined initial $^{53}Mn/^{55}Mn = (4.6 \pm 1.7) \times 10^{-6}$. This value has been recently more precisely measured at $(4.02 \pm 0.26) \times 10^{-6}$ (*Wadhwa et al.,* 2006). This initial ^{53}Mn abundance corresponds to a formation interval $\Delta t_{LEW} = -6 \pm 2$ m.y. relative to the LEW 86010 angrite if ^{53}Mn was homogeneous, implying an "absolute" age of 4564 ± 2 m.y. The initial $^{26}Al/^{27}Al$ ratio of Asuka 881394 is $(1.18 \pm 0.14) \times 10^{-6}$, suggesting a formation time of ~4 m.y. after CAIs, if ^{26}Al was homogeneous. The angrites LEW 86010, D'Orbigny, and Sahara 99555 all contain evidence for live ^{26}Al and ^{53}Mn when they formed. Plagioclase-bearing clasts in the Dar al Gani 319 polymict ureilite yielded an initial $^{26}Al/^{27}Al$ ratio of 4×10^{-7} (*Kita et al.,* 2003). This corresponds to formation ~5 m.y. after CAIs, if an initially homogeneous distribution of ^{26}Al is assumed. The significance of a few-million-year delay between CAI formation and achondrite crystallization is discussed in more detail in section 6.2. Absolute ages also suggest a significant delay between CAI formation and achondrite crystallization. The Pb-Pb mineral isochron ages of cumulate eucrites range from 4.40 G.y. to 4.48 G.y. (*Tera et al.,* 1996). Angrites have an absolute age of 4557.8 ± 0.5 m.y. (*Lugmair and Galer,* 1992), i.e., approximately 10 m.y. younger than CV CAIs. These data imply that the formation of some differentiated asteroids occurred several millions of years after the formation of the first chondritic components.

Recently, *Gounelle and Russell* (2005) have proposed a chronological model based on the assumption that ^{26}Al and ^{53}Mn were heterogeneously distributed in the early solar system. They assume that CAIs and chondrules have intrinsic different initial contents of ^{26}Al and ^{53}Mn, and that differentiated parent bodies are the result of the agglomeration of CAIs and chondrules in chondritic proportions. With such assumptions, it is possible to calculate a model relative age that dates the time difference between the agglomeration of CAIs and chondrules of a given parent body until the isotopic closure after differentiation of that same parent body. Note that the meaning of age in such a model is radically different from that of models assuming a homogeneous distribution of ^{26}Al and ^{53}Mn (see above). In such a model, Asuka 881394 crystallized 2.8 ± 1 m.y. after the agglomeration of its precursors, while D'Orbigny crystallized 4.3 ± 1 m.y. after the crystallization of its precursors. Tying these relative numbers to absolute Pb-Pb ages provides absolute ages for the agglomeration of precursors of Asuka 881394 and D'Orbigny (*Gounelle and Russell,* 2005).

4. SUMMARY OF COSMOCHEMICAL EVIDENCE FOR DISK LIFETIMES

The evidence from several long- and short-lived isotope systems and mineralogical observations suggests that CAIs are the oldest known solids in the solar system. The latest Pb-Pb and petrographic data suggest that the first chondrules may have formed at around the same time as CAI formation (see *Amelin et al.,* 2004; *Bizzarro et al.,* 2004). However, chondrule formation appears to have been a protracted process lasting several millions of years. Since both these components are generally believed to have formed while the solar system had a protoplanetary disk, the most straightforward conclusion that can be drawn is that high-temperature processing in the disk may have taken several millions of years. However, results from the different isotope systems often contradict each other in precise detail. For example, the Pb-Pb system suggests that the maximum age difference between CV3 chondrules and CAIs is 2 m.y. or less, whereas the ^{26}Al data suggest an age gap between CAI formation and formation of the first chondrules of ~>2 m.y. The (albeit limited) recent precise Pb-Pb data points to each of the components of a particular meteorite having a similar age to each other, but differences of 4–5 m.y. are seen in bulk age between meteorites from different groups. In contrast, ^{26}Al-^{26}Mg dating suggests that CAIs from most groups have a similar age, distinguishable from chondrules in the same meteorite groups. While Al-Mg systems suggest a 2–3 m.y. age gap between different components from the meteorite groups, Mn-Cr systematics point to a possibly longer age gap of up to 12 m.y. (again between different meteorite groups). Petrologic evidence suggests that the formation of CAIs and chondrules may have even overlapped, albeit from very rare observations.

Clearly, we are far from having a complete understanding of the chronology of the early solar system, and resolution of these inconsistencies requires a detailed consideration of the weaknesses of each isotopic system as a chronometer and an assessment of their initial distribution. The Mn-Cr system can probably be disregarded as an effective chronometer of the CAI-chondrule age gap, since the primary Mn content of CAIs is so low as to make initial abundance of ^{53}Mn in CAIs problematic. In addition, there is evidence that ^{53}Mn was initially heterogeneous in the solar system (*Shukolyukov and Lugmair,* 2000). Both the Al-Mg and Pb-Pb systems may have been affected by later elemental mobilization, either in the nebula or parent body. This may have caused homogenization of Pb isotopes in the parent body, or preferential resetting of Al-Mg systematics in chondrules rather than in CAIs. A final reason for the discrepancy is that the $^{26}Al/^{27}Al$ of the early solar system may have been heterogeneous, diminishing the use of Al-Mg-isotopic systematics as a chronometer in the context of determining the relative age of CAIs and chondrules.

Two working interpretations of these observations will be considered in section 6 below. First, the isotopic data may point to an extended nebular history for the components of each chondrite class. In this case, a viable storage mechanism for the early-formed components must be considered. A second possibility is that all the components from a single class formed at around the same time, but with individual components having very different ^{26}Al contents (e.g., if the short-lived isotopes formed by irradiation close to a young Sun). In this case, the apparent several-million-year age difference between the chondrite groups (*Amelin et al.,* 2002, 2004) is due to the formation of chondrites, from isotopically heterogeneous components, lasting several millions of years.

While the isotope systems do not yield an entirely consistent picture in detail, all the data point to an extended period of formation of nebular solids that lasted on the order of a few million years. In section 6 we discuss several ways to explain these observations. However, precise quantification of the time periods involved will require further analyses of well-characterized chondrite components on unaltered meteorite samples, using several different isotope techniques (see section 7).

5. OBSERVATIONS OF DISK LIFETIMES AROUND YOUNG STELLAR OBJECTS

Our understanding of the lifetimes of the disks of low-mass, pre-main-sequence stars based on astronomical constraints has changed only modestly since the review by *Podosek and Cassen* (1994). Those authors concluded that the observational evidence was strong for disk lifetimes longer than 1 m.y. but typically less than 10 m.y.; recent research has added a number of details, but has not changed the overall picture.

To understand the limitations of astronomical "disk lifetimes," it is necessary to consider what is actually being observed. To begin with, our ability to detect disk gas is poor, especially molecular hydrogen, the dominant constituent, and so little is known about gas-disk lifetimes. A few estimates of disk gas masses have been made using warm molecular hydrogen emission (e.g., *Thi et al.,* 2001), although at least one detection has been called into question (*Lecavelier des Etangs et al.,* 2001). In any case, these detections do not constrain the amount of material at temperatures much lower than about 100 K; in addition, if the disk is optically thick at mid-infrared wavelengths, as is often the case for T Tauri stars, the observed emission may come only from disk surface layers.

Detections of emission from molecules other than H_2 are much more common. Both hot (1000 K) and cold (10–30 K) CO emission has been detected from disks around T Tauri stars (e.g., *Aikawa et al.,* 2002; *Najita et al.,* 2003), and low-temperature molecular emission has also been studied (e.g., *Dutrey et al.,* 1996). The problem with the detections of molecular emission, apart from abundance uncertainties, is that they generally arise from warm(er) upper layers of T Tauri star disks, due to optical depth effects and requirements for excitation, and thus directly trace only a small fraction of the total gas mass present. The situation is different for the so-called "debris disk" systems such as β Pic, which are relatively optically thin and have small gas masses, but these objects probably represent the very end stages, when collisions between planetesimals probably produce most of the observed emitting dust.

The one set of gas diagnostics that appear to reflect the bulk of local gaseous material are the emission lines produced as disk gas accretes through the stellar magnetosphere and continuum emission produced as the accreting gas crashes onto the stellar surface (Fig. 4). Although the amount of gas in these inner regions is very small, the rate of mass flow onto the star is significant in an evolutionary sense. Estimates indicate that typical mass flow rates are $\sim 10^{-8}$ $M_\odot$ per year, so that over the T Tauri lifetime of a few million years the typical star accretes a few times the minimum mass solar nebula (*Hartmann et al.,* 1998). While this accreted mass must be a typical minimum gas mass of T Tauri disks, the measurement of accreting gas obviously does not directly constrain the instantaneous disk mass.

The main astronomical indicator of disk lifetimes is dust emission. Here one must make additional distinctions, depending upon the wavelength of observation. The most sensitive observations so far have been made at near-infrared wavelengths ($\lambda \sim 2$–3 μm) using groundbased telescopes. However, such data only trace dust in the innermost disk (Fig. 4), typically at a distance of about 0.1 AU for T Tauri stars. Dust appears to sublimate at temperatures of about

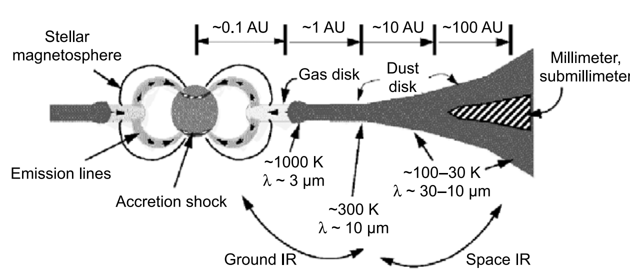

Fig. 4. Schematic diagram of a typical T Tauri star with accretion disk. Differing diagnostics of disks, along with approximate typical distance scales and wavelengths of observation, are indicated. Most infrared dust emission tends to arise from surface layers, due to optical depth effects; submillimeter and millimeter-wave emission is more likely to trace midplane regions where most of the mass resides (see text).

1500 K in pre-main-sequence stellar accretion disks (*Natta et al.,* 2001; *Muzerolle et al.,* 2003), setting the effective inner edge of disk dust. Observations at λ ~ 3 μm generally provide the most sensitive indication of inner dusty disks, especially for T Tauri stars. Groundbased observations on large telescopes can also be used to detect dusty disk emission at λ ~ 10 μm with reasonable sensitivity, probing material at distances of about 1 AU in low-mass systems. Spacebased observations can detect colder dust emission, from regions extending out to a hundred astronomical units or more (Fig. 4). Current datasets from the Infrared Astronomical Satellite (IRAS) and Infrared Space Observatory (ISO) missions provide modest sensitivity to disk emission; forthcoming results from the Spitzer Space Telescope (previously known as the Space Infrared Telescope Facility, or SIRTF) should provide substantial advances in this area. Finally, submillimeter- and millimeter-wave observations can detect the coldest disk dust residing at large distances from the central star. Current sensitivity in this region is limited; the Atacama Large Millimeter Array (ALMA) promises major advances in a few years. Overall, it becomes more difficult to detect dust emission as the wavelength of observation increases, thus our constraints on inner disk dust are much stronger than on outer disk dust.

Dust emission is a poor indicator of disk mass. The shortest-wavelength observations are sensitive to extremely tiny amounts of small dust, but rapidly become insensitive to dust mass for particles much larger than a few micrometers in size. In addition, T Tauri disks are usually optically thick at wavelengths <100 μm; thus, the level of infrared disk emission does not directly reflect the amount of mass, even if the size distribution were known. Submillimeter- and millimeter-wave observations detect more optically thin material, and thus can be used with more certainty to estimate disk masses (e.g., *Beckwith et al.,* 1990), but are subject to substantial uncertainties in the particle size distribution (*D'Alessio et al.,* 2001), and generally do not have sufficient sensitivity to trace disk evolution to smaller masses.

Despite the above caveats, detections of dust emission have played an important role in understanding disk evolution. *Strom et al.* (1989) were the first to constrain the evolution of dusty disk emission, finding that most disks "disappeared" over timescales <10 m.y. Their data indicated a strong decrease in emission from the hottest, innermost disk regions even at ages as young as 3 m.y. *Skrutskie et al.* (1990) performed more sensitive groundbased measurements of mid-infrared emission (λ = 10 μm; Fig. 4), and concluded that about half of all stars exhibited dusty disk emission, while less than 10% of their sample did so at ages >10 m.y. (see review by *Strom et al.,* 1993).

Haisch et al. (2001) studied several young clusters using more sensitive observations in the L-band (3.5-μm wavelength), which essentially probes the inner disk edge (Fig. 4). As indicated by hot disk emission, Haisch et al. inferred that the initial fraction of young stars with dusty disks is high, ≥80% (see also *Hillenbrand et al.,* 1998). At ages of <~3 m.y., the disk fraction was about half, with most disk emission disappearing by about 6 m.y., confirming the results of *Skrutskie et al.* (1990) and *Strom et al.* (1999). No clear evidence has been developed for any difference in disk lifetimes between clustered and dispersed star-forming environments (see also *Brice et al.,* 2001).

There is a generally a close correspondence between the disappearance of inner disk dust emission and the ending of accretion onto the central star (*Hartigan et al.,* 1990; *Muzerolle et al.,* 2000). A notable exception is the older (10 m.y.) T Tauri star TW Hya. As shown in Fig. 5, TW Hya exhibits strong disk emission at long wavelengths, but little

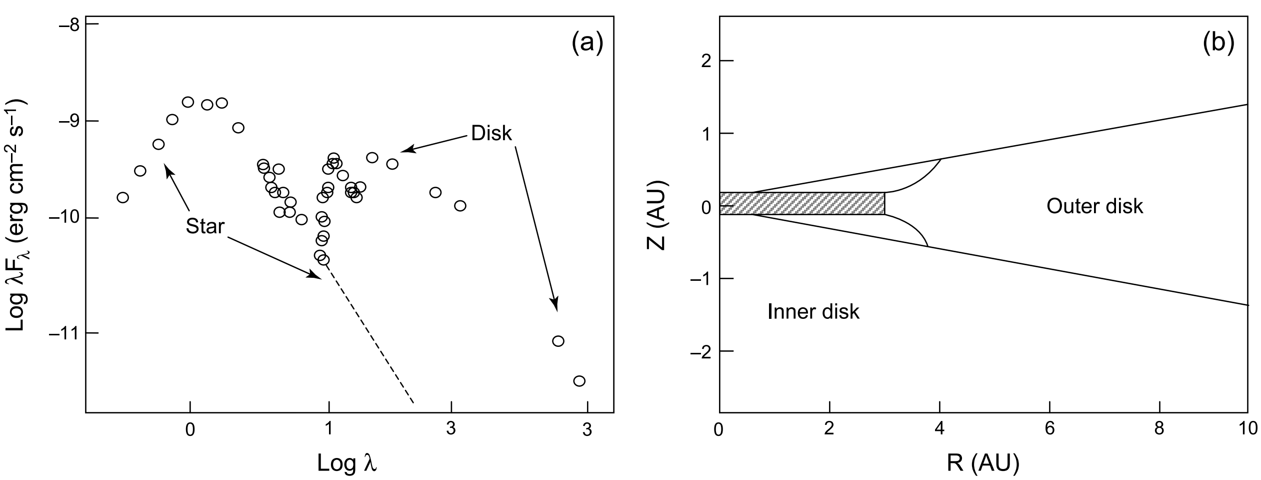

Fig. 5. **(a)** Spectral energy distribution of the 10-m.y.-old star TW Hya. Emission from the dusty disk is strong at wavelengths ≥10 μm, but is nearly absent at shorter wavelengths. **(b)** Models of the spectral energy distribution imply that the disk must be relatively free of small dust particles at radii <4 AU, even though the star is actively accreting, suggesting gas may be present within this "hole" in the dust distribution (see text).

or no hot dust emission. Models of the spectral energy distribution suggest large dust masses beyond 4 AU but very minor amounts of small dust particles within this radius (*Calvet et al.,* 2002). At the same time, TW Hya is accreting gas at highly time-variable rates (*Muzerolle et al.,* 2000; *Alencar and Batalha,* 2002), which suggests that substantial amounts of gas are passing through this region even if small dust is not.

The least-model-dependent way of characterizing the observations of disk emission is to refer to the "disk lifetimes" as the timescale at the wavelength in question when the disk becomes optically thin (e.g., *Strom et al.,* 1989). Objects like TW Hya seem to be rare, suggesting that the timescale for the transition between optically thick and optically thin disk dust emission is very short (*Skrutskie et al.,* 1990). The most straightforward interpretation of the observations is that the disk lifetimes estimated from dust emission basically all correspond to times at which the small particles are incorporated into larger bodies, rather than accretion onto the central star or dispersal. Long-wavelength observations of TW Hya suggest particle growth to sizes of 1 cm or so at radii ~100 AU (*Calvet et al.,* 2002); one would suspect even larger particle growth at smaller distances, where timescales of evolution should be shorter.

The correlation of the decline in infrared emission with the cessation of accretion onto central stars suggests that gas as well as dust is being accumulated. The case of TW Hya is extremely interesting as a transition object in which small dust and gas flow has not completely disappeared.

In summary, between 50% and 80% of low-mass stars initially have circumstellar disks, as indicated by dust emission and stellar accretion. The typical timescale for the disappearance of substantial dust emission and disk is roughly 3–5 m.y.; however, considerable variation in this timescale is seen among individual objects. Very few objects survive with strong dust emission and gas stellar accretion to ages of 10 m.y. These conclusions mostly correspond to disk properties in the inner few astronomical units; more sensitive observations with the Solar Space Telescope (SST) and ALMA should provide better constraints on disk evolution at large radii in a few years. The timescales for evolution on much larger distance scales, and the evolution and ultimate fate of the majority of disk gas (see, e.g., *Hollenbach et al.,* 2000) are poorly understood at present.

6. DYNAMICAL CONSIDERATIONS

The Pb-Pb age data suggest that chondrule formation lasted a few million years after the formation of most CAIs, based on chondrule ages in several different groups (section 2.5). Regardless of the models adopted for the formation of CAIs and chondrules, or the source of the short-lived radioisotope ^{26}Al, there are several known examples of individual objects having a several-million-year nebula history (section 3). As discussed below in section 6.1, there has been concern as to whether individual particles can survive in the nebula for this long. In addition, the formation of planetesimals *too soon* after CAIs may lead to their including so much heat-producing ^{26}Al and ^{60}Fe that far more melted asteroids and meteorites should be observed than actually are. Different scenarios for asteroidal accretion that might account for these observations are discussed in sections 6.2 and 6.3.

6.1. The Role of Nebular Gas

Solid particles in the disk are controlled by their interactions with the gas. Any plausible circumstellar disk is partially supported by a radial pressure gradient, so that it rotates at slightly less than the Kepler velocity. Gas drag acting on particles causes them to drift inward. As described by *Adachi et al.* (1976) and *Weidenschilling* (1977), the peak radial velocity of several tens of meters per second is reached by approximately meter-sized bodies, whose orbits decay at ~1 AU/century. Radial velocities decrease on both sides of this peak, and are approximately proportional (inversely) to size for smaller (larger) bodies. In the absence of other processes, both kilometer-sized planetesimals and millimeter-sized particles would migrate inward 1 AU in ~10^5 yr, while centimeter-sized bodies would travel this distance in ~10^4 yr. These timescales are short compared with the formation intervals and age differences for CAIs and chondrules inferred from ^{26}Al data, causing a concern about their survival. Assuming these age differences are real, two processes that reconcile the theory and observations are discussed in the next two sections.

6.2. Rapid Asteroidal Accretion in Nonturbulent Nebulae

Particle collisions occur due to a variety of processes that operate in different size ranges, including thermal motion, differential settling and radial drift, and turbulence, if present. Assuming that collisions result in coagulation, the timescales for growth can be estimated analytically (*Weidenschilling,* 1988). Because the first aggregates are likely to be porous, crushable particles that can dissipate collisional energy, growth to meter size is likely to be easy regardless of the presence or absence of turbulence (e.g., *Weidenschilling,* 1997). If coagulation is inefficient, growth timescales scale inversely with sticking coefficient (although any sticking coefficient would not be a simple constant, but a function of particle sizes and relative velocities). Various forms of collective effects have been offered that circumvent uncertainties in sticking mechanisms; none of these have been quantified from the standpoint of asteroidal accretion timescales (see *Cuzzi and Weidenschilling,* 2006).

At any heliocentric distance an initial population of micrometer-sized grains can produce centimeter-sized aggregates in a few hundred orbital periods; the principal growth mechanism is sweeping of smaller aggregates by larger ones, which settle more rapidly. If the nebula is nonturbulent, such aggregates settle into a thin layer in the central plane during growth to centimeter sizes.

Size-dependent drift rates cause collisions in any ensemble of particles with a range of sizes. In a nonturbulent nebula, centimeter- to meter-sized particles settle into a fairly dense midplane layer where relative velocities are low and growth is rapid (*Cuzzi et al.,* 1993; *Dobrovolskis et al.,* 1999; *Cuzzi and Weidenschilling,* 2006). For perfect sticking, this process can form kilometer-scale planetesimals in a few thousand orbital periods, i.e., ~10^4 yr in the asteroid region. More detailed numerical modeling (*Weidenschilling,* 1980, 1997) is in good agreement with these estimates, even when realistic collisional properties are assumed rather than perfect sticking. Such growth times are short enough to prevent much loss of solids into the Sun.

A short formation time for planetesimals in the asteroid belt is consistent with the asteroid region initially containing its full complement of solids relative to H/He, with mass exceeding that of Earth, or >10^3× the present mass of the belt. Once kilometer-sized or larger planetesimals formed, this high surface density would result in the rapid gravitational accretion of protoplanetary embryos with masses as large as ~0.01-0.1 $M_\oplus$ on timescales ~10^6 yr, while leaving a significant fraction of the total mass in small bodies. These embryos, and most of the smaller bodies, would be removed on timescales ~10^7–10^8 yr by scattering into unstable resonances with Jupiter and Saturn (*Chambers and Wetherill,* 2001).

However, such rapid formation of planetesimals encounters two potential problems. One is the thermal consequences of rapid accretion of bodies containing ^{26}Al. If planetesimals formed shortly after CAI formation and if ^{26}Al was uniformly distributed in the solar nebula with an initial ^{26}Al/^{27}Al ratio of 5×10^{-5}, still-alive ^{26}Al would heat their interiors enough to reset isotopic ages in bodies as small as ~30 km diameter (*LaTourrette and Wasserburg,* 1998), and would melt larger bodies. The heating effects of ^{60}Fe would be even more significant over longer timescales. It is not clear whether such thermal histories are compatible with the evidence from asteroids and meteorites. Most meteorites show evidence of thermal metamorphism, and a significant fraction of CAIs do appear to have been altered (whether this alteration occurred in the nebula or within parent bodies is unclear) (*Brearley,* 2006). Iron meteorites provide evidence for melting within multiple parent bodies, but only a few studies of formation age have been made (*Suguira and Hoshino,* 2003; *Scherstén et al.,* 2005), and these suggest accretion before ~2 m.y. after CAIs. However, there are very few asteroids that, from spectral interpretations, appear to be differentiated; 4 Vesta is the only surviving large asteroid of these. We believe we have meteoritic samples of 4 Vesta, in the form of HED meteorites, some of which show clear evidence for having initially contained ^{26}Al (*Srinivasan et al.,* 1999; *Nyquist et al.,* 2003a). Hafnium-tungsten isotopes imply that Vesta differentiated ~3 m.y. after CAI formation (*Yin et al.,* 2002), consistent with the amount of active ^{26}Al incorporated in its melts. The stochastic nature of asteroidal accretion allows the growth of Vesta-sized bodies on such a timescale, but the absence of other large igneous asteroids is puzzling, if the accretion timescale for large planetesimals is indeed <10^5 yr. Other achondrite groups (ureilites and angrites) contained ^{26}Al at even lower levels than HEDs when they crystallized (*Kita et al.,* 2003; *Nyquist et al.,* 2003b), although these are more highly evolved rocks that presumably were relatively late to form on their parent bodies. In fact, melted asteroids of any size (and their achondrite meteorites) are in the minority. In general, thermal modeling implies that the initial ^{26}Al/^{27}Al ratio in most parent bodies was much lower than in CAIs, consistent with either a large-scale inhomogeneity in short-lived isotopes across the solar accretion disk, or a delay in the onset of asteroidal accretion (*Bennett and McSween,* 1996; *Ghosh et al.,* 2006).

Another problem with rapid formation of planetesimals is that the apparent CAI-chondrule age difference, the spread in apparent formation ages for different chondrules, and an extended nebular history for some individual objects seem to indicate formation over an interval greater than 1 m.y. If these age differences are real, a simple model in which small solid particles form in the solar nebula and accrete directly into parent bodies of chondritic meteorites is not tenable. Either planetesimal formation had to be delayed, or material that accreted quickly had to be recycled. Preservation of primitive components and isotopic anomalies after such recycling requires that most meteorite parent bodies (i.e., asteroids) accreted from debris of smaller first-generation bodies *that never became hot enough for their isotope systematics to be reset* (i.e., <30 km in diameter). This is discussed in more detail in *Cuzzi and Weidenschilling* (2006). We revisit this concept below, after discussing the role of turbulence.

6.3. Delayed Asteroidal Accretion in Turbulent, Diffusive Nebulae

When, where, and even whether the nebular gas was turbulent continues to be debated (*Stone et al.,* 2000; *Cuzzi et al.,* 2001). The observation that million-year-old disks retain a considerable fraction of material in small dust particles has been used to argue that widespread turbulence must be present at least that long, regardless of our current ignorance about how this is accomplished (*Dullemond and Dominik,* 2005). Turbulence potentially plays a fundamental role in the accretion process, however, as highlighted below. Particle-gas interactions in turbulence are reviewed by *Cuzzi and Weidenschilling* (2006); here, we touch only on some highlights and implications for meteoritic timescales.

6.3.1. Vertical diffusion and growth timescales. Global turbulence diffuses particles into a thick, low-density layer in which particle growth is much slower than in globally nonturbulent nebulae (*Cuzzi et al.,* 1993; *Dubrulle et al.,* 1995; *Dobrovolskis et al.,* 1999; *Cuzzi et al.,* 1996; *Cuzzi and Weidenschilling,* 2006), and meter-sized particles drift into the Sun before growing significantly (*Weidenschilling,* 1988, cf. equation (15)). Naturally, the growth of planetesimals and planetary embryos is thus also frustrated. *Weidenschilling* (2004) has found that the ability to retain enough material in the Kuiper belt region practically requires turbulence to be absent there. However, the situation may be different in the inner solar system where, as noted above, asteroidal and meteoritic evidence suggests that growth needs to be slowed, not enhanced.

6.3.2. Radial diffusion and redistribution of material; application to calcium-aluminum-rich inclusions. Because small particles are quite well trapped to the nebular gas, their random velocities in turbulence are practically the same as the fluctuating gas velocities (10^3–10^4 cm/s), and far exceed their small radial drift velocities (1–10 cm/s). Random motions of this sort, in the presence of a radial gradient in abundance, generate a diffusive mass flux that can easily swamp the mass flux due to inward radial drift. If CAIs are only produced in the inner nebula, an outward gradient will certainly exist, and outward radial diffusion can populate the entire nebula with small particles from the inner nebula; thus "loss into the Sun" is not the problem it once appeared (*Cuzzi et al.,* 2003, 2005). *Bockelée-Morvan et al.* (1995) reached similar conclusions in the context of crystalline silicate grains in comets. Calcium-aluminum-rich inclusions can be formed in the inner solar system and persist for 1–3 m.y. until, or during, the chondrule-formation era. Larger CAIs are not retained as long in this model, which thus predicts that CV chondrites were accumulated earlier than most other meteorite types. There is a hint from the recent work of *Amelin et al.* (2004) that this may indeed be the case. It has also been suggested that CAIs were ejected from the inner solar system on orbital timescales by stellar winds or jets (*Shu et al.,* 1996). Even then, without turbulence, they still drift inward and are lost from the asteroid-belt region on a 10^5 yr or less timescale, thus the transporting wind must have been active for several million years, and accretion must have been fast after emplacement into the asteroid belt. Observation and interpretation of the mineralogy of CAIs might be able to distinguish between these hypotheses (see *Cuzzi and Weidenschilling,* 2006).

In either case, persistence of CAIs as independent nebular constituents requires that they *not* accrete into sizeable planetesimals for the approximately several-million-year chondritic-component-forming period, and suggests that asteroidal accretion might have been *difficult* in the inner solar system for that amount of time. This frustration of accretion is consistent with the apparent delay required in accreting planetesimals large enough to melt under the influence of their ^{26}Al. If CAIs formed early, they might have been absorbed into meter-sized particles, but these either got disrupted and dispersed, evaporated in the inner solar system and got recycled as condensates, or were lost into the Sun, with only the nonaccreted ones surviving.

6.3.3. Recycled planetesimals. An alternative to "storage" of CAIs by outward turbulent diffusion or stellar wind ejection is the rapid formation of planetesimals large enough to be unaffected by the gas drag (at least a few kilometers), so that their orbits do not decay significantly during an interval of ~>1 m.y. Such a scenario would imply the following sequence of events: CAIs form early, perhaps in the hot inner region of the nebula, and are preserved (with less refractory material) within first-generation planetesimals, which are too small to melt. These bodies are later disrupted by collisions, returning CAIs to the nebula and producing large amounts of dust and small fragments. [*Wood* (2004) has noted some difficulties this possibility faces, given the lack of reset Al-Mg ages and the lack of shock features in CAIs.] Some heating mechanism (shock waves?) melts this material, producing chondrules and remelting or altering some CAIs. Chondrules, CAIs, and dust reaccrete to form chondrite parent bodies before the nebula dissipates. In this model, chondrites are secondary products of a complex and violent evolution rather than the first planetesimals to form. The most plausible cause of such events so long after the formation of the solar nebula is the late formation of Jupiter; the model and its implications are explored by *Weidenschilling and Cuzzi* (2006).

The two scenarios of diffusion and recycling are not necessarily mutually exclusive. A period of turbulence could have been followed by asteroidal accretion, with an episode of disruption, processing, and reaccretion after Jupiter formed.

7. SUMMARY AND OPEN QUESTIONS

Cosmochemical measurements and observations of young stellar objects both indicate a disk lifetime of several millions of years. Absolute Pb-Pb measurements of components believed to have formed within the disk point to a minimum duration of 4–5 m.y. Aluminum-26 measurements, less reliable because of questions about its initial distribution, also point to a >5-m.y. age of the solar accretionary disk. This is compatible with known achondrite ages. A disk lifetime of this order seems plausible by comparisons to young stellar objects. The typical disk lifetime (observed from the duration of dust emission) is 3–5 m.y., albeit with a large range of ages between different stars. Preserving nebular components in a disk for this period of time is possible provided that there is a mechanism for preventing the early-formed objects from drifting into the Sun; this could be achieved by turbulent diffusion, or by storing CAIs and early-formed chondrules in planetesimals that were too small to melt.

A number of important open questions on this subject are discussed in *Cuzzi and Weidenschilling* (2006), and *Weidenschilling and Cuzzi* (2006). Some of the outstanding areas are highlighted below.

More measurements of ages of individual components (CAIs and chondrules) within the same meteorite may shed light on asteroidal accretion timescales. It is important to establish if the hints we have seen so far for differences in ages between chondrites is real (*Kunihiro et al.,* 2004; *Amelin et al.,* 2004), and this could potentially lessen the CAI storage problem. One important question is whether the formation of CAIs and chondrules overlapped in time, or if there was a true gap between them. Overlap would suggest that they formed by a single process, perhaps with energy density and temperatures decreasing with time and/or heliocentric distance. An age gap of ~1 m.y. would imply either more than one separate process or the same process occurring multiple times, separated in time by a period of relative inactivity. The distribution of relative ages inferred from ^{26}Al show little overlap between unaltered CAIs and chondrules (*Wadhwa and Russell,* 2000). This distribution appears to favor a gap, but may be due at least in part to selection of types of objects with measurable ^{26}Al ages. Further measurements are required, especially on objects intermediate between CAIs and chondrules. Only three Al-Mg ages exist in the literature for AOAs (*Itoh et al.,* 2002), which are intermediate to CAIs and chondrules in properties and composition. These preliminary measurements on AOAs suggest that they may have formed around 1 half-life (0.7 m.y.) after CAIs, indicating that these objects may "fill the gap" between chondrules and CAIs. Measurements are also required to compare different isotope systems on the same object, and especially to combine absolute age dates by Pb-Pb and Al-Mg and Mn-Cr measurements, in order to establish the distribution of these isotopes in the early solar system.

Continuing studies of asteroid thermal evolution can help to constrain planetesimal accretion timescales. Such studies need to include more realistic physics, such as time-variable growth rates and collisional disruption occurring concurrently with accretion. Associated isotopic analyses of objects as diverse as unequilibrated chondrites to the many different iron cores of differentiated bodies of which we have samples can also help to constrain formation ages.

The distribution and lifetime of cold dusty material around young stars is not currently well constrained. More extensive measurements, particularly of submillimeter- to millimeter-wavelength observations, will allow us to better observe dust at smaller stellocentric distances.

It is critical that we try to understand the prevalence and intensity of turbulence, since it plays a key role in setting the timescales and even radial distribution of planetesimal formation. Theoretical studies of nebula fluid dynamics need to continue, and it may turn out that inferences from various aspects of primitive bodies themselves might help us to understand this issue (*Cuzzi and Weidenschilling,* 2006).

REFERENCES

Adachi I., Hayashi C., and Nakazawa K. (1976) The gas drag effect on the elliptical motion of a solid body in the primordial solar nebula. *Prog. Theor. Phys., 56,* 1756–1771.

Aikawa Y., van Zadelhoff G. J., van Dishoeck E. F., and Herbst E. (2002) Warm molecular layers in protoplanetary disks. *Astron. Astrophys., 386,* 622–632.

Alencar S. H. P. and Batalha C. (2002) Variability of southern T Tauri stars. II. The spectral variability of the classical T Tauri star TW Hydrae. *Astrophys. J., 571,* 378–393.

Allègre C. J., Manhes G., and Gopel C. (1995) The age of the Earth. *Geochim. Cosmochim. Acta, 59,* 1445–1456.

Amelin Y. and Krot A. N. (2005) Young Pb-isotopic ages of chondrules in CB carbonaceous chondrites (abstract). In *Lunar and Planetary Science XXXVI,* Abstract #1247. Lunar and Planetary Institute, Houston (CD-ROM).

Amelin Y., Krot A. N., Hutcheon I. D., and Ulyanov A. A. (2002) Lead isotopic ages of chondrules and calcium-aluminium-rich inclusions. *Science, 297,* 1678–1683.

Amelin Y., Krot A. N., and Twelker E. (2004) Duration of the chondrule formation interval: A Pb isotope study (abstract). *Geochim. Cosmochim. Acta, 68,* A759.

Arnould M., Paulus G., and Meynet G. (1997) Short-lived radionuclide production by non-exploding Wolf-Rayet stars. *Astron. Astrophys., 321,* 452–464.

Beckwith S. V. W., Sargent A. I., Chini R. S., and Guesten R. (1990) A survey for circumstellar disks around young stellar objects. *Astron. J., 99,* 924–945.

Becquerel H. (1896a) On the rays emitted by phosphorescence [translated title]. *Compt. Rendus, 122,* 420–421.

Becquerel H. (1896b) On the invisible rays emitted by phosphorescent bodies [translated title]. *Compt. Rendus, 122,* 501–503.

Bennett M. E. III and McSween H. Y. Jr. (1996) Revised model calculations for the thermal histories of ordinary chondrite parent bodies. *Meteoritics & Planet. Sci., 31,* 783–792.

Birck J.-L. and Allègre C. J. (1988) Manganese-chromium isotope systematics and the development of the early solar system. *Nature, 331,* 579–584.

Bischoff A. and Srinivasan G. (2003) ^{26}Mg excess in hibonites of the Rumuruti chondrite Hughes 030. *Meteoritics & Planet. Sci., 38,* 5–12.

Bizzarro M., Baker J. A., and Haack H. (2004) Mg isotope evidence for contemporaneous formation of chondrules and refractory inclusions. *Nature, 431,* 275.

Bockelée-Morvan D., Brooke T. Y., and Crovisier J. (1995) On the origin of the 3.2 to 3.6 μm emission feature in comets. *Icarus, 133,* 147–162.

Boss A. P. (2004) Evolution of the solar nebula. VI. Mixing and transport of isotopic heterogeneity. *Astrophys. J., 616,* 1265–1277.

Boss A. P. and Vanhala H. A. T. (2001) Origin and early evolution of solid matter in the solar system. *Philos. Trans. R. Soc. Lond., A359,* 2005–2017.

Brearley A. J. (2006) The action of water. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Brice C., Vivas A. K., Calvet N., Hartmann L., Pacheco R., Herrera D., Romero L., Berlind P., Sanchez G., Snyder J. A., and Andrews P. (2001) The CIDA-QUEST large-scale survey of Orion OB1: Evidence for rapid disk dissipation in a dispersed stellar population. *Science, 291,* 93–96.

Busso M., Gallino R., and Wasserburg G. J. (2003) Short-lived nuclei in the early solar system: A low mass stellar source? *Publ. Astron. Soc. Austral., 20,* 356–370.

Calvet N., D'Alessio P., Hartmann L., Wilner D., Walsh A., and Sitko M. (2002) Evidence for a developing gap in a 10 m.y. old protoplanetary disk. *Astrophys. J., 568,* 1008–1016.

Cameron A. G. W., Hoflich P., Myers P. C., and Clayton D. D. (1995) Massive supernovae, Orion gamma rays, and the formation of solar system. *Astrophys. J. Lett., 447,* L53–L57.

Campbell A. J., Humayun M., and Weisberg M. K. (2002) Siderophile element constraints on the formation of metal in the metal-rich chondrites Bencubbin, Weatherford, and Gujba. *Geochim. Cosmochim. Acta, 66,* 647–660.

Chambers J. and Wetherill G. (2001) Planets in the asteroid belt.

Meteoritics & Planet. Sci., 36, 381–399.

Chaussidon M. and Gounelle M. (2006) Irradiation processes in the early solar system. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Chen J. H. and Tilton G. R. (1976) Isotopic lead investigations on the Allende carbonaceous chondrite. *Geochim. Cosmochim. Acta, 40,* 617–634.

Chen J. H. and Wasserburg G. J. (1981) The isotopic composition of U and Pb in Allende inclusions and meteoritic phosphates. *Earth Planet. Sci. Lett., 52,* 1–15.

Consolmagno G. and Drake M. (1977) Composition and evolution of the eucrite parent body — Evidence from rare earth elements. *Geochim. Cosmochim. Acta, 41,* 1271–1282.

Cuzzi J. N. and Weidenschilling S. J. (2006) Particle-gas dynamics and primary accretion. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Cuzzi J. N., Dobrovolskis A. R., and Champney J. M. (1993) Particle gas dynamics in the midplane of a protoplanetary nebula. *Icarus, 106,* 102–134.

Cuzzi J. N., Dobrovolskis A. R., and Hogan R. C. (1996) Turbulence, chondrules and planetesimals. In *Chondrules and the Protoplanetary Disk* (R. H. Hewins et al., eds.,) pp. 35–43. Cambridge Univ., Cambridge.

Cuzzi J. N., Hogan R. C., Paque J. M., and Dobrovolskis A. R. (2001) Size-selective concentration of chondrules and other small particles in protoplanetary nebula turbulence. *Astrophys. J., 546,* 496–508.

Cuzzi J. N., Davis S. S., and Dobrovolskis A. R. (2003) Blowing in the wind. II. Creation and redistribution of refractory inclusions in a turbulent protoplanetary nebula. *Icarus, 166,* 385–402.

Cuzzi J. N., Petaev M., Ciesla F., Krot A. N., and Scott E. R. D. (2005) Nebula models of non-equilibrium mineralogy: Wark-Lovering rims (abstract). In *Lunar and Planetary Science XXXVI,* Abstract #2095. Lunar and Planetary Institute, Houston (CD-ROM).

D'Alessio P., Calvet N., and Hartmann L. (2001) Accretion disks around young objects. III. Grain growth. *Astrophys. J., 553,* 321–334.

Darwin C. (1859) *On the Origin of the Species.* Republished in 1988 by New York Univ., New York. 478 pp.

Desch S. J., Srinivasan G., and Connolly H. C. Jr. (2004) An interstellar origin for the beryllium-10 in CAIs. *Astrophys. J., 602,* 528–542.

Dobrovolskis A. R., Dacles-Mariani J. S., and Cuzzi J. N. (1999) Production and damping of turbulence by particles in the solar nebula. *J. Geophys. Res., 104,* 30805.

Dubrulle B., Morfill G., and Sterzik M. (1995) The dust subdisk in the protoplanetary nebula. *Icarus, 114,* 237–246.

Dullemond C. P. and Dominik C. (2005) Dust coagulation in protoplanetary disks: A rapid depletion of small grains. *Astron. Astrophys., 434,* 971–986.

Dutrey A., Guilloteau S., Duvert G., Prato L., Simon M., Schuster K., and Menard F. (1996) Dust and gas distribution around T Tauri stars in Taurus-Auriga. I. Interferometric 2.7 mm continuum and 13 CO J = 1–0 observations. *Astron. Astrophys., 309,* 493–504.

Endreß M., Zinner E., and Bischoff A. (1996) Early aqueous activity on primitive meteorite parent bodies. *Nature, 379,* 701–703.

Faure G. (1986) *Principles of Isotope Geology*. Wiley, New York. 608 pp.

Fireman E. L., DeFelice J., and Norton E. (1970) Ages of the Allende meteorite. *Geochim. Cosmochim. Acta, 34,* 873–881.

Galy A., Hutcheon I., and Grossman L. (2004) $(^{26}Al/^{27}Al)_0$ of the nebula inferred from Al-Mg systematics in bulk CAIs from CV3 chondrites (abstract). In *Lunar and Planetary Science XXXV,* Abstract #1790. Lunar and Planetary Institute, Houston (CD-ROM).

Ghosh A., Weidenschilling S. J., McSween H. Y. Jr., and Rubin A. (2006) Asteroidal heating and thermal stratification of the asteroid belt. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Gilmour J. D. and Saxton J. M. (2001) A time-scale of formation of the first solids. *Philos. Trans. R. Soc. London, 359,* 2037–2048.

Gilmour J. D., Whitby J. A., Turner G., Bridges J. C., and Hutchison R. (2000) The iodine-xenon system in clasts and chondrules from ordinary chondrites: Implications for early solar system chronology. *Meteoritics & Planet. Sci., 35,* 445–456.

Goswami J. N. and Vanhala H. A. T. (2000) Short-lived nuclides in the early solar system: Meteoritic evidence and plausible sources. In *Protostars and Planets IV* (V. M. Mannings et al., eds.), pp. 963–995. Univ. of Arizona, Tucson.

Goswami J. N., Marhas K. K., and Sahijpal S. (2001) Did solar energetic particles produce the short-lived radionuclides present in the early solar system? *Astrophys. J., 549,* 1151–1159.

Gounelle M. and Russell S. S. (2005) On early solar system chronology: Implications of an heterogeneous spatial distribution of ^{26}Al and ^{53}Mn. *Geochim. Cosmochim. Acta, 69,* 3129–3144.

Gounelle M., Shu F. H., Shang H., Glassgold A. E., Rehm E. K., and Lee T. (2001) Extinct radioactivities and protosolar cosmic-rays: Self-shielding and light elements. *Astrophys. J., 548,* 1051–1070.

Gray C. M., Papanastassiou D., and Wasserburg G. J. (1973) The identification of early condensates from the solar nebula. *Icarus, 20,* 213–239.

Grossman L. (1972) Condensation in the primitive solar nebula. *Geochim. Cosmochim. Acta, 38,* 47–64.

Guan Y., Huss G. R., Leshin L. A., and MacPherson G. J. (2003) Ni isotope anomalies and ^{60}Fe in sulfides from unequilibrated enstatite chondrites (abstract). In *Meteoritics & Planet. Sci., 38,* Abstract #5268.

Haisch K. E., Lada E. A., and Lada C. J. (2001) Disk frequencies and lifetimes in young clusters. *Astrophys. J. Lett., 553,* L153–L156.

Hartigan P., Hartmann L., Kenyon S. J., Strom S. E., and Skrutskie M. F. (1990) Correlations of optical and infrared excesses in T Tauri stars. *Astrophys. J. Lett., 354,* L25–L28.

Hartmann L., Calvet N., Gullbring E., and D'Alessio P. (1998) Accretion and the evolution of T Tauri disks. *Astrophys. J., 495,* 385.

Henderson P. (1982) *Inorganic Geochemistry.* Pergamon, Oxford. 353 pp.

Hillenbrand L. A., Strom S. E., Calvet N., Merrill K. M., Gatley I., Makidon R. B., Meyer M. R., and Skrutskie M. F. (1998) *Astrophys. J., 116,* 1816.

Holmes A. (1946) An estimate of the age of the Earth. *Nature, 57,* 680–684.

Hollenbach D. J., Yorke H. W., and Johnstone D. (2000) Disk dispersal around young stars. In *Protostars and Planets IV* (V. Mannings et al., eds.), pp. 401–428. Univ. of Arizona, Tucson.

Hoppe P., Macdougall J. D., and Lugmair G. W. (2004) High spatial resolution ion microprobe measurements refine chronology of Orgueil carbonate formation (abstract). In *Lunar and Planetary Science XXXV,* Abstract #1313. Lunar and Planetary Institute, Houston (CD-ROM).

Hsu W., Wasserburg G. J., and Huss G. R. (2000) High time resolution by use of the ^{26}Al chronometer in the multistage formation of a CAI. *Earth Planet. Sci. Lett., 182,* 15–29

Huss G. R., MacPherson G. J., Wasserburg G. J., Russell S. S., and Srinivasan G. (2001) Aluminium-26 in calcium-rich inclusions and chondrules from unequilibrated ordinary chondrites. *Meteoritics & Planet. Sci., 36,* 975–997.

Hutcheon I. D., Krot A. N., Marhas K., and Goswami J. (2004) Magnesium isotopic compositions of igneous CAIs in the CR carbonaceous chondrites: Evidence for an early and late-stage melting of CAIs. In *Lunar and Planetary Science XXXV,* Abstract #2124. Lunar and Planetary Institute, Houston (CD-ROM).

Ireland T. R., Compston W., Williams I. S., and Wendt I. (1990) U-Th-Pb systematics of individual perovskite grains from the Allende and Murchison carbonaceous chondrites. *Earth Planet. Sci. Lett., 101,* 379–387.

Itoh S. and Yurimoto H. (2003) Contemporaneous formation of chondrules and refractory inclusions in the early solar system. *Nature, 423,* 728–731.

Itoh S., Rubin A. E., Kojima H., Wasdson J. T., and Yurimoto H. (2002) Amoeboid olivine aggregates and AOA-bearing chondrule from Y-81020 CO 3.0 chondrite: Distribution of oxygen and magnesium isotopes (abstract). In *Lunar and Planetary Science XXXIII,* Abstract #1490. Lunar and Planetary Institute, Houston (CD-ROM).

Kita N. T., Nagahara H., Togashi S., and Morishita Y. (2000) A short duration of chondrule formation in the solar nebula: Evidence from ^{26}Al in Semarkona ferromagnesian chondrules. *Geochim. Cosmochim. Acta, 64,* 3913–3922.

Kita N. T., Ikeda Y., Shimoda H., Morishita Y., and Togashi S. (2003) Timing of basaltic volcanism in ureilite parent body inferred from the ^{26}Al ages of plagioclase-bearing clasts in DaG-319 polymict ureilite (abstract). In *Lunar and Planetary Science XXXII,* Abstract #1557. Lunar and Planetary Institute, Houston (CD-ROM).

Krot A. N. and Keil K. (2002) Anorthite-rich chondrules in CR and CH carbonaceous chondrites: Genetic link between Ca, Al-rich inclusions and ferromagnesian chondrules. *Meteoritics & Planet. Sci., 37,* 91–111.

Krot A. N., Hutcheon I. D., and Keil K. (2002) Anorthite-rich chondrules in the reduced CV chondrites: Evidence for complex formation history and genetic links between CAIs and ferromagnesian chondrules. *Meteoritics & Planet. Sci., 37,* 155–182.

Krot A. N., McKeegan K. D., Huss G. R., Liffman K., Sahijpal S., Hutcheon I. D., Srinivasan G., Bischoff A., and Keil K. (2004) Aluminum-magnesium and oxygen isotope study of relict Ca-Al-rich inclusions in chondrules. *Astrophys. J.,* in press.

Krot A. N., Yurimoto H., Hutcheon I. D., and MacPherson G. J. (2005a) Relative chronology of CAI and chondrule formation: Evidence from chondrule-bearing igneous CAIs. *Nature, 434,* 998–1001.

Krot A. N., Amelin Y., Cassen P., and Meibom A. (2005b) Young chondrules in CB chondrites from a giant impact in the early solar system. *Nature, 436,* 989–992.

Krot A. N., Hutcheon I. D., Brearley A. J., Pravdivtseva O. V., Petaev M. I., and Hohenberg C. M. (2006) Timescales and settings for alteration of chondritic meteorites. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Kunihiro T., Rubin A. E., McKeegan K. D., and Wasson J. T. (2004) Initial ^{26}Al/^{27}Al in carbonaceous-chondrite chondrules: Too little ^{26}Al to melt asteroids. *Geochim. Cosmochim. Acta, 68,* 2947–2957.

LaTourrette T. and Wasserburg G. J. (1998) Mg diffusion in anorthite: Implications for the formation of early solar system planetesimals. *Earth Planet. Sci. Lett., 158,* 91–108.

Lecavelier des Etangs A. and 13 colleagues (2001) Deficiency of molecular hydrogen in the disk of β Pictoris. *Nature, 412,* 706–708.

Lee T., Papanastassiou D. A., and Wasserburg G. J. (1976) Demonstration of ^{26}Mg excess in Allende and evidence for ^{26}Al. *Geophys. Res. Lett., 3,* 109–112.

Lee T., Shu F. H., Shang H., Glassgold A. E., and Rehm K. E. (1998) Protostellar cosmic rays and extinct radioactivities in meteorites. *Astrophys. J., 506,* 892–912.

Leya I., Halliday A. N., and Wieler R. (2003) The predictable collateral consequences of nucleosynthesis by spallation reactions in the early solar system. *Astrophys. J., 594,* 605–616.

Lugmair G. W. and Gailer S. J. G. (1992) Age and isotopic relationships among the angrites Lewis Cliff 86010 and Angra dos Reis. *Geochim. Cosmochim. Acta, 56,* 1673–1694.

Lugmair G. W. and Shukolyukov A. (1998) Early solar system timescales according to ^{53}Mn-^{53}Mn systematics. *Geochim. Cosmochim. Acta, 62,* 2863–2886.

MacPherson G. J., Wark D. A., and Armstrong J. T. (1988) Primitive material surviving in chondirtes: Refractory inclusions. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds), pp. 746–807. Univ. of Arizona, Tucson.

MacPherson G. J., Davis A. M., and Grossman J. N. (1989) Refractory inclusions in the unique chondrite ALH85085 (abstract). In *Meteoritics, 24,* 297.

MacPherson G. J., Davis A. M., and Zinner E. K. (1995) The distribution of aluminum-26 in the early solar system: A reappraisal. *Meteoritics, 30,* 365–386.

Manhès G., Göpel C., and Allègre C. (1988) Systematique U-Pb dans les inclusions refractaires d'Allende: Le plus vieux materiau solaire. *Compt. Rend. de l'ATP Planetol.,* 323–327.

McKeegan K. D. and Davis A. M. (2003) Early solar system chronology. In *Treatise on Geochemistry, Vol. 1: Meteorites, Comets, and Planets* (A. M. Davis, ed.), pp. 431–461. Elsevier, Oxford.

McKeegan K. D., Chaussidon M., and Robert F. (2000) Incorporation of short-lived ^{10}Be in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science, 289,* 1334–1337.

McKeegan K. D., Greenwood J. P., Leshin L. A., and Cosarinsky M. (2001) Abundance of ^{26}Al in ferromagnesian chondrules of unequilibrated ordinary chondrites (abstract). In *Lunar and Planetary Science XXXII,* Abstract #2009. Lunar and Planetary Institute, Houston (CD-ROM).

Mostefaoui S., Kita N. T., Togashi S., Tachinaba S., Nagahara H., and Morishita Y. (2002) The relative formation ages of ferromagnesian chondrules inferred from their initial aluminium-26/aluminium-27 ratios. *Meteoritics & Planet. Sci., 37,* 421–438.

Mostefaoui S., Lugmair G. W., Hoppe P. and El Goresy A. (2003) Evidence for live iron-60 in Semarkona and Chervony Kut: A Nanosims study (abstract). In *Lunar and Planetary Science XXXIV,* Abstract #1585. Lunar and Planetary Institute, Houston (CD-ROM).

Mostefaoui S., Lugmair G. W., and Hoppe P. (2004) In-situ evidence for live ^{60}Fe in the solar system: A potential heat source for planetary differentiation from a nearby supernova explosion (abstract). In *Lunar and Planetary Science XXXV,* Abstract #1271. Lunar and Planetary Institute, Houston (CD-ROM).

Muzerolle J., Calvet N., Brice C., Hartmann L., and Hillenbrand L. (2000) Disk accretion in the 10 m.y. old T Tauri stars TW Hydrae and Hen 3-600A. *Astrophys. J. Lett., 535,* L47–L50.

Muzerolle J., Calvet N., Hartmann L., and D'Alessio P. (2003) Unveiling the inner disk structure of T Tauri stars. *Astrophys. J. Lett., 597,* L149–L152.

Najita J., Carr J. S., and Mathieu R. D. (2003) Gas in the terrestrial planet region of disks: CO fundamental emission from T Tauri stars. *Astrophys. J., 589,* 931–952.

Natta A., Prusti T., Neri R., Wooden D., Grinin V. P., and Mannings V. (2001) A reconsideration of disk properties in Herbig Ae stars. *Astron. Astrophys., 371,* 186–197.

Nyquist L., Lindstrom D., Wiesman H., Martinez R., Bansal B., Mittlefehldt D., Shih C-Y., and Wentworth S. (1994) Mn-Cr systematics of individual Chainpur chondrules. *Meteoritics, 29,* 512.

Nyquist L., Lindstrom D., Mittlefehldt D., Shih C.-Y., Wiesmann H., Wentworth S., and Martinez R. (2001) Manganese-chromium formation intervals for chondrules from the Bishunpur and Chainpur meteorites. *Meteoritics & Planet. Sci., 36,* 911–938.

Nyquist L. E., Reese Y., Wiesmann H., Shih C.-Y., and Takeda H. (2003a) Fossil ^{26}Al and ^{53}Mn in the Asuka 881394 eucrite: Evidence of the earliest crust on asteroid 4 Vesta. *Earth Planet. Sci. Lett., 214,* 11–25.

Nyquist L., Shih C. Y., Wiesmann H., and Mikouchi T. (2003b) Fossil ^{26}Al and ^{53}Mn in Orbigny and Sahara 99555 and the timescale for angrite magmatism (abstract). In *Lunar and Planetary Science XXXII,* Abstract #1388. Lunar and Planetary Institute, Houston (CD-ROM).

Papanastassiou D. A., Bogdanovski O., and Wasserburg G. J. (2002) ^{53}Mn-^{53}Cr systematics in Allende refractory inclusions (abstract). In *Meteoritics & Planet. Sci., 36,* A114.

Patterson C. C. (1956) Age of meteorites and the Earth. *Geochim. Cosmochim. Acta, 10,* 230–237.

Patterson C. C., Tilton G. R., and Inghram M. G. (1955) Age of the Earth. *Science, 121,* 69–75.

Podosek F. A., Zinner E. K., MacPherson G. J., Lundberg L. L., Brannon J. C., and Fahey A. J. (1991) Correlated study of initial Sr-87/Sr-86 and Al-Mg isotopic systematics and petrologic properties in a suite of refractory inclusions from the Allende meteorite. *Geochim. Cosmochim. Acta., 55,* 1083–1110.

Podosek F. A. and Cassen P. (1994) Theoretical, observational, and isotopic estimates of the lifetime of the solar nebula. *Meteoritics, 29,* 6–25.

Rubin A. E., Kallemeyn G. W., Wasson J. T., Clayton R. N., Mayeda T. K., Grady M., Verchovsky A. B., Eugster O., and Lorenzetti S. (2003) Formation of metal and silicate globules in Gujba: A new Bencubbin-like meteorite fall. *Geochim. Cosmochim. Acta, 67,* 3283–3298.

Russell S. S., Srinivasan G., Huss G. R., Wasserburg G. J., and MacPherson G. J. (1996) Evidence for widespread ^{26}Al in the solar nebula and constraints for nebula time scales. *Science, 273,* 757–762.

Russell S. S., Huss G. R., Fahey A. J., Greenwood R. C., Hutchison R., and Wasserburg G. J. (1998) An isotopic and petrologic study of calcium-aluminum-rich inclusions from CO3 meteorites. *Geochim. Cosmochim. Acta, 62,* 689–714.

Russell S. S., Gounelle M., and Hutchison R. (2001) Origin of short-lived radionuclides. *Philos. Trans. R. Soc. Lond., A359,* 1991–2004.

Rutherford E. (1929) Origin of actinium and the age of the Earth. *Nature, 123,* 313–314.

Rutherford E. and Boltwood B. (1905) The relative proportion of radium and uranium in radio-active minerals. *Am. J. Sci., 20,* 55–56.

Scherstén A., Elliott T., Hawkesworth C. J., Russell S. S., and Masarik J. (2005) Rapid differentiation of small planets, high precision evidence from Hf-W chronometry. *European Geophysical Union Abstracts, 7,* EGU05-A-05462. European Geosciences Union, Vienna.

Srinivasan G., Goswami J. N., and Bhandari N. (1999) ^{26}Al in eucrite Piplia Kalan: Plausible heat source and formation chronology. *Science, 284,* 1348–1350.

Shu F. H., Shang H., and Lee T. (1996) Toward an astrophysical theory of chondrites. *Science, 271,* 1545–1552.

Shu F. H., Shang S., Gounelle M., Glassgold A. E., and Lee T. (2001) The origin of chondrules and refractory inclusions in chondritic meteorites. *Astrophys. J., 548,* 1029–1050.

Shukolyukov A. and Lugmair G. W. (2000) On the ^{53}Mn heterogeneity in the early solar system. *Space Sci. Rev., 92,* 225–236.

Skrutskie M. F., Dutkevitch D., Strom S. E., Edwards S., Strom K. M., and Shure M. A. (1990) A sensitive 10-micron search for emission arising from circumstellar dust associated with solar-type pre-main-sequence stars. *Astron. J., 99,* 1187–1195.

Stone J. M., Gammie C. F., Balbus S. A., and Hawley J. F. (2000) Transport processes in protostellar disks. In *Protostars and Planets IV* (V. Mannings et al., eds.), pp. 589–611. Univ. of Arizona, Tucson.

Strom K. M., Strom S. E., Edwards S., Cabrit S., and Skrutskie M. F. (1989) Circumstellar material associated with solar-type pre-main-sequence stars — A possible constraint on the timescale for planet building. *Astron. J., 97,* 1451–1470.

Strom S. E., Edwards S., and Skrutskie M. F. (1993) Evolutionary time scales for circumstellar disks associated with intermediate- and solar-type stars. In *Protostars and Planets III* (E. H. Levy and J. I. Lunine, eds.), pp. 837–866. Univ. of Arizona, Tucson.

Sugiura N. and Hoshino H. (2003) Mn-Cr chronology of five IIIAB iron meteorites. *Meteoritics & Planet. Sci., 38,* 117–144.

Swindle T. D., Davis A. M., Hohenberg C. M., MacPherson G. J., and Nyquist L. E. (1996) Formation times of chondrules and Ca-Al-rich inclusions: Constraints from short-lived nuclides. In *Chondrules and the Protoplanetary Disk* (R. H. Hewins et al., eds.), pp. 77–87. Cambridge Univ., Cambridge.

Tachibana S. and Huss G. R. (2003) The initial abundance of ^{60}Fe in the solar system. *Astrophys. J. Lett., 588*, L41–L44.

Tachibana S., Nagahara H., Mostefaoui S., and Kita N. T. (2003) Correlation between relative ages inferred from ^{26}Al and bulk compositions of ferromagnesian chondrules in least equilibrated ordinary chondrites. *Meteoritics & Planet. Sci., 38,* 939–963.

Tachibana S., Huss G. R., Kita N. T., Shimoda H., and Morishita Y. (2005) The abundance of iron-60 in pyroxene chondrules from unequilibrated ordinary chondrites (abstract). In *Lunar and Planetary Science XXXVI,* Abstract #1529. Lunar and Planetary Institute, Houston (CD-ROM).

Tatsumoto M., Unruh D. M., and Desborough G. A.. (1976) U-Th-Pb and Rb-Sr systematics of Allende and U-Th-Pb systematics of Orgueil. *Geochim. Cosmochim. Acta, 40,* 617–634.

Tera F., Carlson R. W., and Boctor N. Z. (1996) Radiometric ages of basaltic achondrites and their relation to the early history of the solar system. *Geochim. Cosmochim. Acta, 61,* 1713–1731.

Thi W. F., Blake G. A., van Dishoeck E. F., van Zadelhoff G. J., Horn J. M. M., Becklin E. E., Mannings V., Sargent A. I., van den Ancker M. E., and Natta A. (2001) Substantial reservoirs of molecular hydrogen in the debris disks around young stars. *Nature, 409,* 60–63.

Thomson W. (Lord Kelvin) (1897) The age of the Earth as an abode for life. *Philos. Mag., 47,* 66–90.

Tilton G. R. (1988a) Radiometric dating. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds), pp. 249–256. Univ. of Arizona, Tucson.

Tilton G. R. (1988b) Age of the solar system. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 257–275. Univ. of Arizona, Tucson.

Turner G. (1970) $^{40}Ar/^{39}Ar$ dating of lunar rock samples. *Science, 167,* 3918.

Vanhala H. A. T. (2001) Injection of radioactivities into the forming solar system: High resolution simulations (abstract). In *Lunar and Planetary Science XXXII,* Abstract #1170. Lunar and Planetary Institute, Houston (CD-ROM).

Vanhala H. A. T. and Boss A. (2002) Injection of radioactivities into the forming solar system. *Astrophys. J., 575,* 1144–1150.

Yin Q., Jacobsen S. B., Yamashita K., Blichert-Toft J., Télouk P., and Albarède F. (2002) A short timescale for terrestrial planet formation from Hf-W chronometry of meteorites. *Nature, 418,* 949–952.

Wadhwa M. and Lugmair G. W. (1996) Age of the eucrite 'Caldera' from convergence of long-lived and short-lived chronometers. *Geochim. Cosmochim. Acta, 60,* 4889–4893.

Wadhwa M. and Russell S. S. (2000) Timescales of accretion and differentiation in the early solar system: The meteoritic evidence. In *Protostars and Planets IV* (V. M. Mannings et al., eds.), pp. 1017–1029. Univ. of Arizona, Tucson.

Wadhwa M., Amelin A., Bogdanovski O., Shukolyukov A., and Lugmair G. (2005) High precision relative and absolute ages for Asuka 881394, a unique and ancient basalt (abstract). In *Lunar and Planetary Science XXXVI,* Abstract #2126. Lunar and Planetary Institute, Houston (CD-ROM).

Wadhwa M., Srinivasan S., and Carlson R. W. (2006) Timescales of planetesimal differentiation in the early solar system. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.), this volume. Univ. of Arizona, Tucson.

Wark D. A. (1987) Plagioclase-rich inclusions in carbonaceous chondrite meteorites: Liquid condensates? *Geochim. Cosmochim. Acta, 51,* 221–242.

Weber D., Zinner E. K., and Bischoff A. (1995) Trace element abundances and magnesium, calcium, and titanium isotopic compositions of grossite-containing inclusions from the carbonaceous chondrite Acfer 182. *Geochim. Cosmochim. Acta, 59,* 803–823.

Weidenschilling S. J. (1977) Aerodynamic of solid bodies in the solar nebula. *Mon. Not. R. Astron. Soc., 180,* 57–70.

Weidenschilling S. J. (1980) Dust to planetesimals — Settling and coagulation in the solar nebula. *Icarus, 44,* 172–189.

Weidenschilling S. J. (1988) Formation processes and time scales for meteorite parent bodies. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 348–371. Univ. of Arizona, Tucson.

Weidenschilling S. J. (1997) When the dust settles — Fractal aggregates and planetesimal formation (abstract). In *Lunar and Planetary Science XXVIII,* p. 517. Lunar and Planetary Institute, Houston.

Weidenschilling S. J. (2004) From icy grains to comets. In *Comets II* (M. C. Festou et al., eds.), pp. 97–104. Univ. of Arizona, Tucson.

Weidenschilling S. J. and Cuzzi J. N. (2006) Accretion dynamics and timescales: Relation to chondrites. In *Meteorites and the Early Solar System II* (D. S. Lauretta and H. Y. McSween Jr., eds.,) this volume. Univ. of Arizona, Tucson.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Sugiura N., Zashu S., and Ebihara M. (2001) A new metal-rich chondrite grouplet. *Meteoritics & Planet. Sci., 36,* 401–418.

Whitby J., Gilmour J. D., Turner G., Prinz M., and Ash R. D. (2002) Iodine-xenon dating of chondrules from the Qingzhen and Kota Kota enstatite chondrites. *Geochim. Cosmochim. Acta, 66,* 347–359.

Whitby J., Russell S. S., Turner G., and Gilmour J. D. (2004) I-Xe measurements of CAIs and chondrules from the CV3 chondrites Mokoia and Vigarano. *Meteoritics & Planet. Sci., 39,* 1387–1403.

Wood J. A. (2004) Formation of chondritic refractory inclusions: The astrophysical setting. *Geochim. Cosmochim. Acta, 68,* 4007–4021.

Young E. D., Simon J. I., Galy A., Russell S. S., Tonui E., and Lovera O. (2005) Supra-canonical $^{26}Al/^{27}Al$ and the thermal evolution residence time of CAIs in the solar protoplanetary disk nebula. *Science, 308,* 223–227.