Chronological Constraints on Planetesimal Accretion

Robert H. Nichols Jr.
Washington University

This chapter provides a brief overview of the timescales associated with the accretion (assemblage) of planetesimals (asteroidal-sized objects on the order of 10–100 km in diameter) in the early solar system based primarily on meteoritic studies, but also on dynamical and astronomical constraints. In the first edition of this book (*Kerridge and Matthews,* 1988) results from each these fields (meteoritic, theoretical, and astronomical) were consistent with a short, dominant planetesimal accretion period, ΔT_{acc} ~ 10 m.y. within the formation of the first solids in the early solar system, and with a precision in each field on the order of a few million years. The more precise limits available now follow the same general trend as before, ΔT_{acc}(dynamic) ≤ ΔT_{acc}(meteoritic) ≤ ΔT_{acc}(astronomical), with this order being dictated primarily by the available precision in each field and by the specifics of the objects being measured and/or the events that are modeled. Meteoritic constraints suggest that initial planetesimal formation (e.g., 4 Vesta, the presumed HED parent body) easily occurred within ~5 m.y. of the formation of the first solar system solids, and more likely within 1–2 m.y. Recent astronomical measurements have also shortened the likely accretion period, and more specifically point to the nebular clearing of dust to 6 m.y. Dynamical considerations, in particular within the context of extrasolar planet modeling, can potentially push planetesimal accretion to within a few 10–100 k.y. Such rapid "primary" formation timescales from each discipline are contrasted with meteoritic evidence for continued "secondary" accretionary processing for periods of 10–100 m.y., as suggested by measurements of precompaction regolith exposure ages, compaction ages, and impact-related events.

1. INTRODUCTION

The epochs in the formation of the early solar system as laid out by the organizational section headings in this book are not necessarily chronologically disjoint spans of time, i.e., they may overlap, often to uncertain extents depending on one's interest, definition, perspective, and available precision. Such is indeed the case for the planetesimal accretion epoch. In a broad sense the onset of planetesimal accretion could begin with the *onset* of the accretion of the nebular gas into the protoplanetary Sun, roughly coinciding with the formation of the first solids in the solar system. Similarly, again in the broadest sense, this epoch is still ongoing given the presence of planetesimal-sized objects in the present-day solar system that are often mutually interacting — e.g., asteroids, comets, Triton, and arguably Pluto — and that are potentially accreting material still, albeit at extremely low rates. The present population of asteroids has indeed evolved through relatively recent impacts and gravitational reaccretion, some within the last 6 m.y. (e.g., *Nesvorný et al.,* 2002). While such a working definition may be of interest to some, it is obviously of little use for our particular interest in the early solar system, other than providing the first, and rather loose, constraint on the duration of accretion of planetesimals, an upper limit of ~4.5 G.y. Herein the emphasis is rather on the timescales (onset, duration, and termination) for the formation of the *first* asteroidal-sized objects (tens of meters to >100 km) in the early solar system primarily in the context of meteoritic records but also with regard to dynamical models of the solar nebula and astronomical observations of circumstellar disk lifetimes.

Most, if not all, variations on the standard paradigm of planetesimal accretion follow a similar framework, although the factors influencing the rate of accretion may vary widely from study to study. From a dynamical perspective primary planetesimal formation may generally be divided into three initial stages coinciding with (1) gravitational collapse of gas and dust; (2) the coagulation of submicrometer- and micrometer-sized grains into centimeter-sized aggregates as gas and dust settle onto the midplane of the nebula (cf. *Russell et al.,* 2006), followed by the gas-drag-induced collisional growth of centimeter- to meter-sized objects (cf. *Cuzzi and Weidenschilling,* 2006); and (3) the gravitational accretion of objects larger than ~10–100 m (cf. *Weidenschilling,* 2000; *Weidenschilling and Cuzzi,* 2006). During stage 3 planetesimal growth may continue to a size less than or equal to that of a planetary precursor or protoplanet, i.e., a body large enough, on the order of 10–100 km in diameter, to undergo melting and metal-silicate differentiation, taken herein to be equivalent to core formation. While the primary accretion process for asteroids presently residing at 3 AU may have ceased before a planet could be formed in that region, it is possible that planet-sized bodies did form in the asteroid belt, but were subsequently removed dynamically (e.g., *Wetherill,* 1992; *Petit et al.,* 2001). The post-

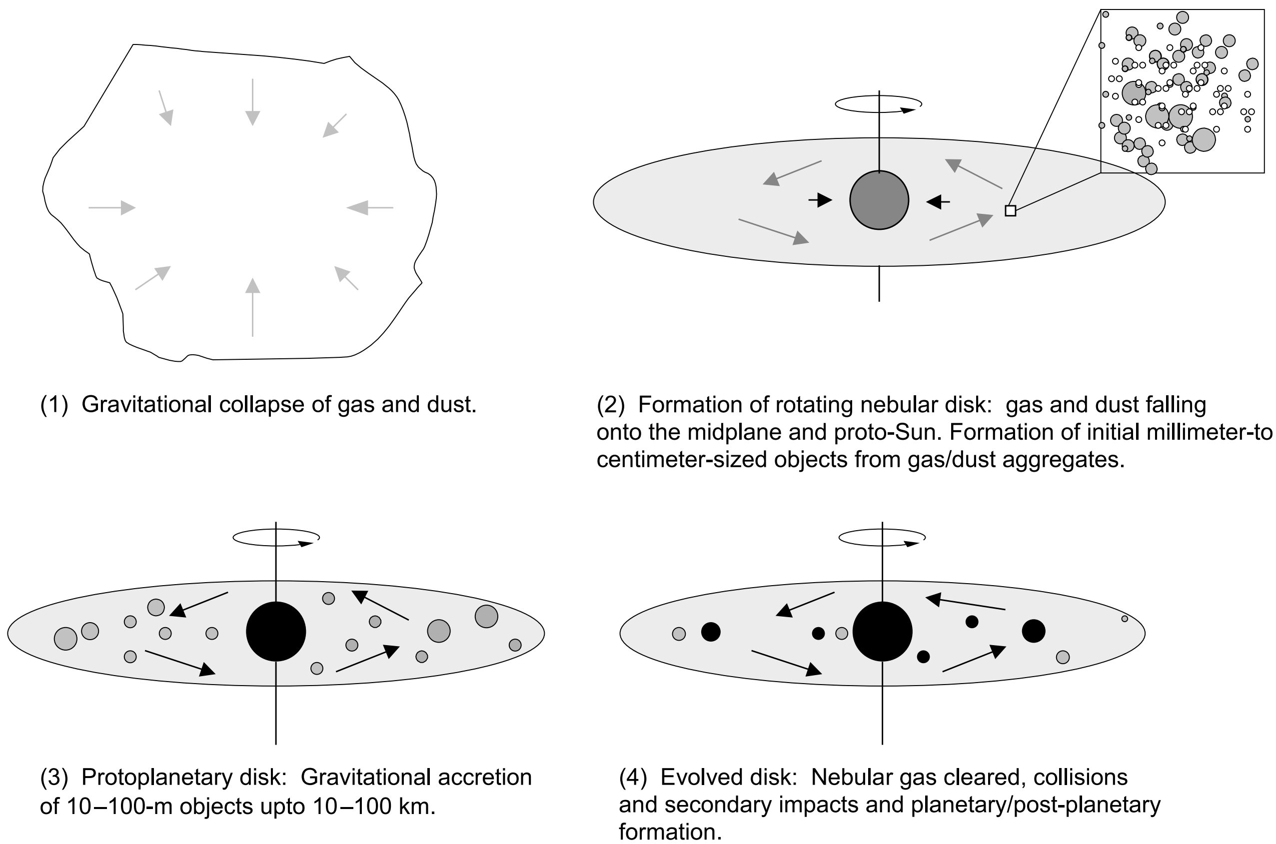

Fig. 1. Depiction of four (1–4) dynamical stages of nebular evolution (see text): (1) gravitational collapse of gas and dust; (2) the coagulation of submicrometer- and micrometer-sized grains into centimeter-sized aggregates as gas and dust settle onto the midplane of the nebula, followed by growth of centimeter- to meter-sized objects; (3) the gravitational accretion of objects larger than ~10–100 m, up to planetesimal size, or 10–100 km; and (4) planetary and post-planetary processing.

primary accretion stage (4) coincides with subsequent collisions and impacts within the asteroid belt over the course of the solar system's history, clearly altering to some degree the first generation of planetesimals (see, e.g., *Turner,* 1988; *Bischoff et al.,* 2006).

A graphical depiction for each of these stages (1–4) is illustrated in Fig. 1. From a dynamical perspective, the onset of each stage could formally be associated with a specific physical parameter and perhaps with a specific point in time. In the present context, however, the adjacent stages are assumed to overlap to some extent based on available precision (ranging from ~100–1000 k.y., see below), with the first three stages occurring in the presence of a nebular gas and dust, and the last stage (planetary formation and secondary planetary processing) occurring after the nebular had cleared. The topic herein, the timing of the onset of primary planetesimal accretion (stage 3), thus occurs in the presence of a nebula prior to the formation of planetary-sized bodies (stage 4). (The duration of the solar nebula is a topic that is beyond this discussion; the reader is referred to the chapters in Parts III–V of this volume.)

1.2. Constraining Planetesimal Accretion: The Problem

Each of these stages of planetesimal accretion potentially lends itself to the formation or processing of macroscopic objects that may be found in meteorites and that may still be sufficiently pristine to shed light on the timeline for primary accretion. In particular, the objects of interest, either isolated from meteorites or whole meteorites themselves, are those whose formation effectively coincides with the rapid isotopic closure or resetting of some radiometric system, thereby permitting object formation to be dated by either absolute or relative isotope dating techniques. These objects include primary nebular condensates that formed near or at the beginning of stages 1 or 2 of planetesimal accretion described above such as individual mineral grains, calcium-aluminum-rich inclusions (CAIs), and chondrules (cf. *Russell et al.,* 2006). Other common objects that are dated are associated with secondary processes such as aqueous alteration and thermal and impact metamorphism (cf. *Krot et al.,* 2006) and differentiation (cf. *Wadhwa et al.,* 2006), all of which potentially postdate stage 3 and the cessation of primary accretion.

The subtle point, and hence the problem, is that chronometric techniques thus applied only set upper limits for the duration of the primary accretion, which may, as will be shown on the basis of dynamical and other arguments, have likely proceeded on a much more rapid timescale. This point may also be rephrased in that our sampling of meteoritic material is likely biased and may have not yet provided us with information directly related to the earliest accretionary events (cf. *Wetherill and Chapman,* 1988). Unlike the events and processes that are dated above (such as the formation of isotopic reservoirs associated with differentiation or isotopic closure associated with mineral formation), the accretionary process itself offers few similarly well-defined, rapid closure events clearly marking either its onset or its termination for any given planetesimal associated with a specific meteorite type. Processes directly associated with early accretion, e.g., impacts, regolith mixing, and breccia formation, are probably insufficiently energetic to set or reset isotopic clocks on the scale of a parent body, and are likely to be subsequently masked by parent-body-wide processes such as the formation of isotopic reservoirs due to differentiation. Accretionary processes, if recorded, tend to reflect episodic secondary processing of the larger bodies that postdates the primary accretion phase and may effectively wipe away any record of the primary accretion process. Thus, while the dating of such secondary events may provide an estimate for the duration of all (primary and secondary) planetesimal accretion in the early solar system, such chronometry in general offers few clues to the timescales associated with initial planetesimal accretion.

In this chapter boundary conditions for the duration of primary planetesimal accretion for objects up to ~100 km in size will be reviewed based on a variety of radiometric, dynamical, and astronomical techniques. While many of these topics are discussed in more detail elsewhere within this book, they are not specifically discussed as a group or in regard to planetesimal accretion. A summary of the primary results is provided in Table 1. Given the paucity of available radiometric limits directly related to primary planetesimal accretion, appeal will also be made to two lesser-studied techniques, "precompaction" exposure to energetic particles and compaction ages, to attempt to set tighter constraints on the duration of planetesimal accretion, in particular for the carbonaceous chondrites.

2. PRIMARY PLANETESIMAL ACCRETION

2.1. The First Solids

The inferred presence of several short-lived nuclides extant within solids at their formation in the early solar system, in particular ^{41}Ca ($T_{1/2}$ ~ 0.1 m.y.) (*Srinivasan et al.,* 1994, 1996), suggests that the formation of these first solids must have occurred relatively quickly (within ~1 m.y.) after the stellar nucleosynthesis of these radioactive nuclei (cf. *Meyer and Clayton,* 2000). While a weaker case may be made for the "local" production of some these short-lived nuclei in the early solar system via an energetic particle irradiation from a "T-Tauri" Sun (e.g., *Chaussidon and Gounelle,* 2006), such a scenario does not preclude the formation of solids very early on (within 1 m.y. of the onset of nebular collapse). In either case the reference point for the formation of these first solar system condensates is generally taken to be the formation of "normal" calcium-aluminum-rich inclusions (CAIs).

Lead-lead measurements of CAIs from the CV chondrite Allende indicate formation at 4.566 ± 0.002 Ga (*Manhès et al.,* 1988; *Göpel et al.,* 1991, 1994; *Allègre et al.,* 1995). More recent and more precise Pb-Pb measurements of similar CAIs from the CV chondrite Efremovka indicate formation at 4.5672 ± 0.0006 Ga (*Amelin et al.,* 2002). While the impressive ±0.6 Ma precision of this Pb-Pb measurement is the most precise age determined to date for the oldest nebular condensates in the solar system using any absolute or long-lived chronometer (see, e.g., *Chen and Tilton,* 1976; *Tatsumoto et al.,* 1976; *Chen and Wasserburg,* 1981) appeal to shorter-lived nuclides is required to narrow the formation interval for the first nebular condensates.

The interval over which "normal" CAIs formed appears to be quite short (<~0.5 m.y.), primarily based on the narrow range of initial ^{26}Al/^{27}Al ratios [$T_{1/2}$(^{26}Al) = 0.74 m.y.] in these objects (*MacPherson et al.,* 1995). Given the likelihood that these CAIs are nebular products (and not produced by planetesimal/planetary processes as may arguably be the case for chondrules as noted below) and that they are likely the oldest objects available for dating in the solar system, the narrow 500 k.y. interval at an age of 4.5672 ± 0.0006 Ga has traditionally been taken to be coincident with the onset of planetesimal accretion, at least from an experimental standpoint; any real formation interval for CAIs has been *assumed* to be negligible given the precision of the isotopic measurements. While it is possible that CAIs existed in the nebula for up to a few million years before planetesimals formed (if, for example, nebula turbulence prevented the aggregation of millimeter-sized solids into larger bodies for protracted periods of time), there is, however, at the present time, little isotopic data supporting this. For comparison, dynamical models of nebular collapse and grain formation up to ~CAI-sized objects commonly require only on the order of ~1 k.y. or less (cf. *Boss,* 2003; *Weidenschilling,* 2000; *Weidenschilling and Cuzzi,* 2006).

With the advent of higher-precision analytic instruments, the assumption of negligibility may not hold. Work on the ^{26}Al-^{26}Mg system (e.g., *Bizzarro et al.,* 2004) suggests that all CAIs formed within the quite narrow span of ~50 k.y., generally consistent with previous work, thereby potentially providing the most precise experimentally derived temporal anchor for the early solar system to date. *Young et al.* (2005), however, suggest that the "canonical" initial ^{26}Al/^{27}Al used in all previous studies is due to a CAI formation

TABLE 1. Chronological constraints on the accretion of 10–100-km-sized planetesimals (and larger objects for comparison) in the early solar system after the formation of CAIs, and estimated formation durations for selected objects.

Meteoritic Constraints			
		Radiometric Technique	References
Fiducial point: CAI formation	4.5672 ± 0.0006 G.y.	Pb-Pb	[1]
CAI formation duration	50 k.y.	Pb-Pb	[2]
	300 ± 100 k.y.	Al-Mg	[3]
	~500 k.y.	Pb-Pb	[1]
Formation of parent bodies (10–100 km)	~5–10 m.y.	^{26}Al, ^{60}Fe heat sources	see text
HED parent body (Vesta, 525 km)	2 m.y.	Mn-Cr	[4]
	4.2 ± 1.3 m.y.	Hf-W	[5]
	~5 m.y.	Hf-W	[5,6]
	5 m.y.	Al-Mg	[7]
H chondrites	3 m.y.	^{244}Pu, ^{40}Ar-^{39}Ar	[8]
Iron meteorite parent body	1–2 m.y.	Al-Mg, Hf-W	[9,10]
Mars (6800 km)	13 ± 2 m.y.	Hf-W	[5]
Earth (12,756 km)	33 ± 2	Hf-W	[5]
Chondrite parent-body formation duration	2.5 m.y.	Pb-Pb	[1,11,12]
Iron meteorite parent-body formation duration	5 m.y.	Re-Os	[13]
Dynamical Constraints			
		Heliocentric Distance	
10–100 km	~1–10 k.y.		
1–10 km to Moon (3476 km)/Mars (6794 km)	~100 k.y.	at 1 AU	[14]
Mercury (4880 km)/Mars (6794 km)	~100 k.y.		
Earth (12,756 km)	~100 m.y.		
Ceres-sized (933 km)	~50 k.y.	at 1 AU	[14]
	~500 k.y.	at 2 AU	
	~5 m.y.	at 2.5 AU	
Gas giants (for comparison)	~1–10 k.y.		[15]
Astronomical Constraints			
		Technique	
Circumstellar Disk Lifetimes	~5–15 m.y.	IR, millimeter, submillimeter emission	[16,17]
	3–6 m.y.	IR, millimeter, submillimeter emission	[18]

References: [1] *Amelin et al.* (2002); [2] *Bizzarro et al.* (2004); [3] *Young et al.* (2005); [4] *Lugmair and Shykolyukov* (1998); [5] *Kleine et al.* (2002); [6] *Kleine et al.* (2004); [7] *Srinivasan et al.* (1999); [8] *Trieloff et al.* (2003); [9] *Bizzarro et al.* (2005); [10] *Kleine et al.* (2005); [11] *Bizzarro et al.* (2004); [12] *Kunihiro et al.* (2004); [13] *Horan et al.* (1998); [14] *Kortenkamp et al.* (2001); [15] *Boss* (2003); [16] *Strom et al.* (1989); [17] *Skrutskie et al.* (1990); [18] *Haisch et al.* (2001).

interval of 300 ± 100 k.y. Until similarly precise measurements are performed on suites of whole-rock objects dating differentiation, the discussion herein remains effectively unchanged.

All other potential nebular condensates, e.g., chondrules, have formation ages that postdate CAI formation by at least ~1 m.y. and likely range up to 2–3 m.y. later (e.g., *Russell et al.,* 1996; *Kita et al.,* 2000; *Amelin et al.,* 2002; *Kunihiro et al.,* 2004; *Bizzarro et al.,* 2004). By definition the formation of chondrules must predate the "final" assemblage of their respective chondritic parent bodies. Formation ages for the oldest chondrules may be contemporaneous at least with the presence of potentially large planetesimals, based on some dynamical models requiring rapid accretion on the order of 1 m.y. (cf. below) and not radiometric constraints. Unfortunately, there is currently no consensus on how planetesimals formed, nor how long the process took (cf. *Chambers,* 2006). If it could be shown, however, that the "chondrule-forming process" requires the presence of a first generation of planetesimals of at least a given size that formed early on, as some "chondrules-forming scenarios" require, then the formation interval between CAIs and chondrules may provide one of the most stringent radiometric limits on how rapidly accretion did occur. Any physical link between the chondrule formation process and the process of planetesimal accretion is, however, only tenuous at this time and the reader is referred to a variety of reviews on this subject (*Grossman,* 1988; *Hewins et al.,* 1996).

2.2. Planetesimal Heating, Differentiation, and Core Formation

Given the presence of millimeter- to centimeter-sized dust in the solar nebula at ~4.5672 Ga (taken herein to be the fiducial point marking the effective onset of planetesimal accretion), a second, later reference point is required to mark the end of the accretion of the first planetesimals. In addition to the rocky planets, several parent bodies were sufficiently large (~10–100 km) to have undergone differentiation, reflected by the fact that many meteorites show evidence that they were partially or totally molten on their parent planetesimals (e.g. *Scott,* 1979). The heating mechanism and its products provide key chronometric constraints for the onset and duration of planetesimal accretion based on (1) the heat source itself, (2) elemental separation occurring between mineral at the onset of melting, and (3) isotopic closure in minerals as the objects cooled, all of which potentially lend themselves to several short- and long-lived chronometric techniques. The subtleties of the different chronometric techniques will not be reviewed here; for this the reader is referred to each of the other chronological chapters within this volume and references therein. As a general rule, however, if it may be assumed that many of the short-lived nuclides were homogeneously distributed in the solar system, then the tightest constraints may be derived from those nuclides that can easily date the formation of isotopic reservoirs, e.g., ^{26}Al, ^{53}Mn, and possibly ^{182}Hf, rather than those radiometric systems that date isotopic closure occurred after an object has cooled, e.g., K-Ar, Rb-Sr, Sm-Nd, I-Xe, and Pb-Pb. This distinction can lead to differences of several millions of years for the formation of a single object.

2.2.1. Planetesimal heat source. A variety of heat sources have been proposed to explain the partial or total melting of the planetesimals including short-lived nuclei radioactive decay (e.g., *Lee et al.,* 1976), electromagnetic induction heating (cf. *Sonnet and Reynolds,* 1979), and accretion of small objects preheated in the nebula (*Larimer and Anders,* 1967). Other potential heat sources include the accretion process itself and associated impacts, as well as heating by the decay of long-lived nuclides. These latter sources, however, appear to be only effective on a terrestrial planet scale whereby mantle melting and mantel metal-silicate differentiation can be driven by impacts that are substantially more energetic than those occurring during initial planetesimal formation.

Of these mechanisms the most plausible heat source appears to be the decay of short-lived nuclides, dominated by that of ^{26}Al (*Lee et al.,* 1976; *Herndon and Herndon,* 1977; *Hutcheon and Hutchison,* 1989; *Zinner and Göpel,* 2002) and possibly to a lesser degree ^{60}Fe ($T_{1/2}$ = 1.5 m.y.) (*Birck and Lugmair,* 1988). *Mostefaoui et al.* (2004) revised the initial abundance of ^{60}Fe upward such that ^{60}Fe may be considered a more important heat source (see also *Moynier et al.,* 2005; *Quitté et al.,* 2005), while the ^{26}Al abundance in some of the most primitive chondrites may, however, have been too low to cause planet-wide heating (*Kunihiro et al.,* 2004). In either case, the accretion of planetesimals would thus need to occur early and rapidly, before these heat sources had decayed, thereby constraining assemblage periods to within a few half-lives of ^{26}Al and ^{60}Fe, translating to within 5–10 m.y. after CAI formation for objects on the order of 10–100 km (e.g., *Wood,* 2000).

2.2.2. The earliest formation ages. The 5–10-m.y. constraint noted above has been well known for some period of time (*Lee et al.,* 1976), and has been confirmed by many model radiometric age measurements of basaltic meteorites over the last 30 years. The majority of these measurements, as evidenced by the compilation of *MacPherson et al.* (1995), has been performed on the ^{26}Al-^{26}Mg system, e.g., *Hutcheon and Hutchison* (1989), *Russell et al.* (1996), *Kita et al.* (2000), *Nyquist et al.* (2003), *Kunihiro et al.* (2004), and *Bizzarro et al.* (2004), and perhaps provides the most robust age information about processes in the early solar system. Other radiometric systems, such as ^{53}Mn-^{53}Cr (e.g., *Lugmair and Shukolyukov,* 1998), I-Xe (cf. *Gilmour,* 2000), and ^{182}Hf-^{182}W (cf. *Horan et al.,* 1998; *Halliday,* 2000; *Halliday et al.,* 2003; *Kleine et al.,* 2002, 2004), yield results that are consistent with the 5–10-m.y. constraint. Herein only a few of the tightest constraints will be noted; for more detailed discussion of these and other isotopic systems the reader is referred to *Wadhwa et al.* (2006) and *Halliday* (2006).

The initial ^{26}Al/^{27}Al ratio measured in the basaltic eucrite Piplia Kalan indicates that its HED (howardite-eucrite-diogenite) parent object, presumably the ~250-km asteroid "4 Vesta" (*McCord et al.,* 1970; *Binzel and Xu,* 1993), melted and differentiated within ~5 m.y. of CAI formation (*Srinivasan et al.,* 1999). Recent measurements of ^{244}Pu fission-track and ^{40}Ar-^{39}Ar thermochronologies of unshocked H chondrites indicate rapid accretion of 100-km-sized objects within 3 m.y. of CAI formation and provides some of the most substantial support for an ^{26}Al heat source (*Trieloff et al.,* 2003), although heat by impact cannot be ruled out (e.g., *Rubin,* 2004). The ^{182}Hf-^{182}W system (*Kleine et al.,* 2002, 2004) indicates that core formation occurred relatively quickly after the formation of CAIs: 4.2 ± 1.3 m.y.

for "4 Vesta," 13 ± 2 m.y. for Mars, and 33 ± 2 m.y. for Earth; on Mars, mantle-crust differentiation and core formation may have been coeval.

An even earlier differentiation (~2 m.y.) for the basaltic achondrite parent body (Vesta) has been inferred based on the ^{53}Mn-^{53}Cr chronometer (*Lugmair and Shukolyukov,* 1998). They obtained a Mn-Cr age of ~4565 Ma from a eucrite whole-rock isochron (which is ~2 m.y. younger than the Pb-Pb age for CAIs). The same authors, however, argue that the solar system might be older than that given by the Pb-Pb age of CAIs. Using their 4571-Ma estimate for the upper age limit of the solar system would give an age for Vesta's mantle of ~6 Ma. Recent ^{26}Al-^{26}Mg and ^{182}Hf-^{182}W measurements on iron meteorites further indicate that the differentiation of their parent asteroids occurred within 1–2 m.y. after CAI formation (e.g., *Bizzarro et al.,* 2005; *Kleine et al.,* 2005).

For many of these objects differentiation does not coincide with any solar-system-wide cessation of planetesimal accretion. For example, the accretion of the chondrite parent bodies has been inferred to have lasted for a period of at least 2.5 m.y. following CAI formation (*Amelin et al.,* 2002; *Bizzarro et al.,* 2004; *Kunihiro et al.,* 2004). For the bulk of the iron meteorites an accretion period of ~5 m.y. has been inferred (*Horan et al.,* 1998). While protracted accretion rates for objects larger than planetesimals based on Hf-W have been suggested by *Halliday* (2000, 2006), the radiometric data alone do not preclude the accretion of a given object having terminated substantially earlier than its model radiometric differentiation age.

2.3. Dynamical Constraints

Many conventional dynamical models of planetesimal/planetary formation suggest an early and rapid period of accretion, commonly referred to as "runaway growth" (e.g., *Weidenschilling and Cuzzi,* 2006). More precisely, the term "runaway growth" usually does not apply to the formation of 1–10-km planetesimals, but rather their subsequent growth when gravitational interactions between the solid bodies become significant. Most, if not all, of these models independently point to the rapid formation of bodies 1–10 km up to Moon/Mars-sized bodies within ~0.1 m.y. at 1 AU. As an example, one recent theoretical model for the growth of planetesimals and planets (*Kortenkamp et al.,* 2001) indicates extremely rapid formation of 10–100-km planetesimals within 10^4 yr, Mercury- and Mars-sized objects within 10^5 yr, and Earth-sized objects within 10^8 yr, with the rates being contingent on heliocentric distance. In the region of the asteroid belt (~3 AU) strong perturbations with massive gas giants may limit the rate of growth such that several Ceres-sized objects (~900 km) could form at 1 AU within 0.05 m.y., at 1.5 AU within 0.5 m.y., at 2 AU within 1 m.y., and 2.5 AU in 5 m.y. Alternatively, the effects of "dynamical friction," on which "runaway growth" is likely attributed, may also be significantly diminished at 3 AU compared to 1 AU due to lower nebular surface densities and orbital periods (e.g., *Weidenschilling,* 2000; *Wetherill and Inaba,* 2000). The potentially rapid accretion and differentiation in asteroids and the terrestrial planets (e.g., *Kleine et al.,* 2002) taken on its own would indicate that the accretionary process has an effective early termination point (cf. *Boss,* 2003, *Boss and Goswami,* 2006; *Weidenschilling,* 2000; *Weidenschilling and Cuzzi,* 2006). Even more rapid formation timescales within 1000 yr have been developed for the outer planets around massive stars (*Boss,* 2003), but such models are generally focused on giant-planet formation and are not directly relevant to the type of planetesimal accretion discussed herein.

2.4. Astronomical Constraints

Measurements of infrared (~micrometer), submillimeter, and millimeter emission in low- to intermediate-mass circumstellar disks have long suggested disk lifetimes on the order of ~5–15 m.y. (e.g., *Strom et al.,* 1989; *Skrutskie et al.,* 1990), which are consistent with the typical ~10-m.y. lifetime of the solar nebular accretion disk inferred from meteoritic analyses (cf. *Podosek and Cassen,* 1994). A recent astronomical survey of circumstellar disks around young clusters of stars (*Haisch et al.,* 2001) indicates that all stars within a given cluster lose their disks within ~6 m.y. of formation and half within 3 m.y. While this is the tightest astronomical constraint to date for nebular clearing and may be coincident with the cessation of planetesimal accretion, it again only places an upper limit on planetesimal accretion timescales. The distinction must be made between the duration of the nebula, inferred from the presence of dust, and the timescales for the formation of the first planetesimals. The presence of micrometer- to millimeter-sized grains at 10 Ma does not preclude the presence of large (1–100 km) objects, or even planets, that formed early on (e.g., *Natta et al.,* 2000). Poynting-Robertson lifetimes of micrometer-sized dust less than ~10^5 yr coupled with the persistence of dust to 5–10 m.y. suggests that micrometer-sized grains must be replenished by some source, presumably collisions of planetesimal-sized objects (e.g., *Beckwith et al.,* 1990; *Strom*, 1995).

3. POST-PRIMARY ACCRETION

Upper limits for the duration of post-primary accretion events, i.e., stage 4 (Fig. 1), associated with parent-body regolith formation, brecciation, and final compaction of the meteorite may be estimated by a several chronometric methods, including galactic-cosmic-ray (GCR) exposure, fission track dating, and ^{40}Ar-^{39}Ar chronometry. The time at which a meteorite was assembled in its present form on its parent body prior to its final ejection is commonly referred to as its "compaction age." Prior to compaction the meteorite constituents (individual grains, clasts, etc.) may have also been at times in sufficiently close proximity (a few meters) to the near surface of the parent body in its regolith, created by the process of accretion and associated impacts, to record exposure to energetic GCRs. The duration of the residence of meteorite constituents at the near-surface is referred to as its "precompaction age." This age is a lower limit to the time period between formation of the meteorite constituents (either in the nebula or on the parent body) and compaction of the meteorite.

The techniques for measuring precompaction exposure ages based on GCR spallation reactions and compaction ages based primarily on fission track dating are thoroughly covered in *Caffee et al.* (1988) and *Caffee and MacDougall* (1988) and will not be discussed here. Furthermore, only a few new measurements have been reported since the first volume of this book (*Kerridge and Matthews,* 1988). Lower limits on precompaction exposure ages for the CI and CM parent bodies still range from a few million years up to possibly 100 m.y., respectively (*Hohenberg et al.,* 1990; *Nichols et al.,* 1992). While these ages do provide loose limits on the extent of regolith residence and mixing, uncertainties in the energy and flux of solar energetic particles (SCRs) in the early solar system relative to GCRs in the early solar system can introduce factors of a few into the errors on these ages (*Caffee et al.,* 1987; see also *Chaussidon and Gounelle,* 2006). Furthermore, the spallogenic reactions associated with precompaction ages are not energetic enough to reset any other standard radiometric clock, thereby making it difficult or impossible to corroborate the ages.

Macdougall and Kothari (1976) utilized the fission-track method on a suite of mineral grains from CM meteorites, yielding compaction ages on the order of 100–200 m.y. following CAI formation. The technique is limited in that Pu/U fractionation and the presence of actinide-rich matrix adjacent to grains can affect the ages by factors of a few (e.g., *Crozaz et al.,* 1989). A more precise measurement for the compaction age of Orgueil (CI), ~10–15 m.y., utilized Rb-Sr dating of carbonates (*Madougall et al.,* 1984; cf. *Caffee and MacDougall,* 1988), consistent with the few-million-year precompaction exposure noted above. Unfortunately, no known meteorites to date exhibit the characteristics of Orgueil (large, Rb-rich aqueous veins) necessary for a Rb-Sr compaction age determination.

Argon-40–argon-39 chronometry has provided a much larger suite of estimates for post-primary accretion events. Various classes of meteorites exhibit "brecciated" structures, or mixtures of rocks with varying lithologies, created from impacts on parent bodies (cf. *Bischoff et al.,* 2006). The details of "brecciation classification" is often more complicated than a simple single-stage accretionary process, as the parent bodies may have been partially to completely destroyed and reassembled, perhaps multiple times. The presence of brecciated and shocked meteorites and reset radiometric clocks [e.g., ^{40}Ar-^{39}Ar (*Bogard and Garrison,* 2003)] clearly indicate that accretion, disassembly, reaccretion, and impact events have occurred at least for some 50–500 m.y. after CAI formation, culminating with a major period of asteroidal disruption commonly referred to as the "late heavy bombardment" (e.g., *Kring and Cohen,* 2002). Some unbrecciated meteorites, e.g., the Shallowater aubrite, also exhibit complex stages of formation, reassembly, and episodic cooling histories (*Keil et al.,* 1989). Such post-planetary processing, however, makes it difficult to delineate the records associated with the duration of initial accretion, especially when overlain with secondary alteration (cf. *Krot et al.,* 2006), complex cooling histories, and uncertain peak metamorphic temperatures (cf. *Huss et al.,* 2006).

4. SUMMARY

The objective herein has been to present a brief overview of the recent chronological constraints of the accretion of 10–100-km-sized planetesimals in the early solar system as determined by meteoritic, dynamical, and astronomical studies. With advances and increased precision in each field since the first volume of this book (*Kerridge and Matthews,* 1988), the initial planetesimal accretion timescale has become somewhat shorter than 10 m.y.: astronomical to ~5 m.y. from the onset of first solid formation, meteoritic to ~1–2 m.y., and dynamical potentially to less than 1 m.y. (Table 1). While the estimates differ, this is primarily due again to the precision available in each field, or within a field due to the specific objects that are being measured, modeled, or observed. Taken together, it is likely that some planetesimals formed rapidly within 1 m.y. and that the dominant phase of planetesimal accretion occurred within a few million years after the formation of the first solids in the solar system.

At this time it is uncertain whether additional advances and increased precision within each of these fields will be able to significantly improve on what we know about this subject. In the astronomical field, perhaps, room is available for the discovery of solar-type systems whose nebulae clear on timescales significantly shorter than the current ~6-m.y. limit. Whether our solar system acted as fast would still remain uncertain, as is the case for dynamical models that can push planetesimal accretion to a few 10–100 k.y. In the meteoritic field, a combination of increased radiometric precision (substantially less than 1 m.y. for suites of chronometers that can be compared directly with one another) and additional measurements may provide more stringent constraints, but this remains to be seen.

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