

The Early Evolution of the Inner Solar System: A Meteoritic Perspective

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Formation of the solar system may have been triggered by a stellar wind. From then on, the solar system would have followed a conventional evolutionary path, including the formation of a disk and bipolar jets. The now extinct short-lived radionuclides beryllium-10 and, possibly, manganese-53 that were present in meteorites probably resulted from energetic particle irradiation within the solar system. Calcium-aluminum-rich inclusions (the oldest known solar system solids) and chondrules could have been produced by the bipolar jets, but it is more likely that they formed during localized events in the asteroid belt. The chondritic meteorites formed within the temperature range (100 to 400 kelvin) inferred for the midplane of classical T Tauri disks at 2 to 3 astronomical units from their central stars. However, these meteorites may retain a chemical memory of earlier times when midplane temperatures were much higher. Dissipation of the solar nebula occurred within a few million years of solar system formation, whereas differentiation of asteroidal-sized bodies occurred within 5 to 15 million years. The terrestrial planets took \sim 100 million years to form. Consequently, they would have accreted already differentiated bodies, and their final assembly was not completed until after the solar nebula had dispersed. This implies that water-bearing asteroids and/or icy planetesimals that formed near Jupiter are the likely sources of Earth's water.

stronomical observations of molecular clouds and young stellar objects (YSOs, which include protostar, disk, and infalling envelope) provide evidence of the earliest evolutionary stages that the solar system would have passed through (Table 1). The first stage is the contraction of a molecular cloud core to form a YSO (1). The quiescent contraction of a core takes $\sim 10^6$ to 10^7 years, although swifter collapse (~10⁵ years) may be triggered by interstellar shock waves. Once a central protostar has developed, the evolution of YSOs by accretion of the surrounding envelope of molecular cloud material is relatively rapid. In the process, because most cores have some angular momentum, a disk develops around the protostar. Once it does, essentially all material that is subsequently accreted by the star must pass through the disk.

Astronomers divide YSOs into four classes (0 to III). Class 0 objects are deeply embedded in their envelopes and most of the circumstellar mass is in the envelope rather than in a disk. Bipolar jets and associated molecular outflows are ubiquitous in these objects, but they decline in frequency in classes I to III. There is also a copious production of x-rays and MeV-energy particles that continues into the class III phase. Class I objects have more diffuse envelopes. They are characterized by so-called FU Orionis outbursts that are produced by a buildup of material in the disk until instabilities precipitate a burst of accretion onto the star (2). By the end of this phase, a protostar will have essentially reached its final mass. Class II objects are pre-main sequence, classical T Tauri stars. They have lost most of their envelope but still retain well-developed disks. Measured disk masses range from 10^{-3} to 1 solar masses (M_{\odot}) but are typically $\sim 0.02 \ M_{\odot}$ (3). This is similar to the lower limit for estimates of the minimum mass solar nebula required to produce the planets (4). The classical T Tauri phase typically lasts for a few million years (5), although it can be over in as little as 105 years. Class III objects are weak-line T Tauri stars and have little or no evidence of a disk.

At present, we must rely on theoretical models to understand the internal structure and evolution of disks. Of particular importance here are the temperatures at the midplane where high dust densities promote planetesimal formation. On the basis of the measured surface temperatures for T Tauri disks, models suggest that midplane temperatures are 200 to 800 K at 1 astronomical unit (AU) and 100 to 400 K at 2.5 AU from the stars (δ). These are the regions where Earth and most meteorites, respectively, formed. Dissipation of gravitational energy associated with the infall of material onto the disk is the

principal cause of heating. Consequently, the disk surface and midplane temperatures should increase with increasing disk mass accretion rate. At the higher accretion rates of earlier phases of YSO evolution, radial thermal gradients would have been steeper, with midplane temperatures perhaps reaching 800 to 1200 K even at 2.5 AU from the star (2, 6, 7). At temperatures above 1200 to 1300 K, which are possible at <1 to 2 AU from the star, most of the dust would vaporize. During an FU Orionis outburst, midplane temperatures do not increase beyond a few tenths of an AU from the protostar (2).

Starting from tiny dust particles, the asteroids and terrestrial planets formed by collisional aggregation into larger and larger objects. This growth process is generally divided into three stages: (i) aggregation of μ m-sized dust to 1- to 10-km-diameter planetesimals (8), (ii) runaway growth of the largest planetesimals to form planetary embryos (9), and (iii) aggregation of embryos to form the terrestrial planets (10).

Coagulation and sticking of dust particles dominate the first and least understood stage of planet growth. Brownian motion, turbulence, differential settling toward the midplane, and differential radial migration all play a role depending on the particle sizes and the physical conditions. This stage may limit the onset of planetesimal/planet formation. Turbulence frustrates formation of large aggregates (~cm) through collisional destruction and by preventing particles smaller than 1 cm across from settling to the midplane. However, weak turbulence can concentrate particles in eddies (11). If these particle clusters are coherent, they could become the building blocks of planetesimals by settling to the midplane and accreting to one another. Conditions may be weakly turbulent only after disk accretion rates have fallen to low levels, most likely in the T Tauri phase.

Once cm-sized and larger objects can form and settle to the midplane, it may only take a few times 10^5 years to produce kmsized objects. Growth needs to be rapid, otherwise cm- to tens of m-sized objects in the inner solar system would be lost to the Sun (Fig. 1). The influence of gravity becomes important once planetesimals exceed 1 km in diameter. The interactions between planetesimals cause a runaway growth of the largest object in a region, ultimately producing Moon- to Mercury-sized planetary embryos (~ 10^{26} g). At 1 AU from the Sun, this stage

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lasts $\sim 10^5$ years, and at 2 to 3 AU from the Sun, it lasts $\sim 10^6$ years. In the final stage of terrestrial planet formation, growth is more oligarchic and violent, as embryos accrete one another in giant impacts, producing two to four planets after $\sim 10^8$ years.

The growth from 1- to 10-km-diameter to embryo-sized bodies is \sim 30 to 50% efficient; the remainder goes into the Sun or is expelled from the solar system, suggesting that the inner solar nebula was at least two to three times as massive as the minimum mass nebula. Also, although there is a tendency for a planet to grow from embryos that formed near its final position, it accretes material from throughout the inner solar system. Generally, embryos that formed farthest from a protoplanet will be accreted later. If there is a radial gradient in the compositions of embryos, a planet's composition will evolve as it grows. This is often referred to as heterogeneous accretion. However, given the energy involved in the accretion of planetary embryos, temporary magma oceans that erase any chemical memory of this heterogenous accretion seem unavoidable. Evidence for magma oceans on the Moon and Mars is strong, so the lack of clear evidence for one on Earth remains a puzzle (12). More prolonged accumulation of smaller bodies, particularly those arriving after planetary core formation, could leave a compositional signature (socalled late veneer). Finally, embryos in the asteroid belt (located at \sim 2 to 3.5 AU from the Sun) tend to scatter themselves and smaller bodies into resonances with Jupiter and are then ejected from the region (13). This explains why the asteroids constitute $\sim 0.1\%$ of the mass expected for the minimum mass solar nebula.

The Fossil Record

There was a radial temperature gradient when the planets formed. The abundance of a relatively volatile species such as water [condensation temperature (T) ~ 160 K] makes for an obvious distinction between the volatile-depleted terrestrial planets and asteroids on the one hand and the Jovian planets and their icy satellites on the other. The thermal gradient would have been steeper in the terrestrial planet region. However, deciphering solar nebular conditions from the terrestrial planets is difficult because of (i) their broad feeding zones, including the possible accretion of volatile species from comets; (ii) impact processes (14); and (iii) the complex histories of planetary atmospheres (15) that are major volatile reservoirs.

Asteroids will have formed in much more localized zones, and they are less likely to have experienced the extensive reprocessing that affected the larger terrestrial planets. There is a compositional gradient in the asteroid belt (16) and most meteorites, which are our only, albeit biased, samples of the asteroid belt, are primitive.

Meteorites. Chondrites are the most common and the most primitive type of meteorite. Nevertheless, they have been modified to varying degrees by processes that occurred in their parent asteroids, such as aqueous alteration, thermal metamorphism, and shock metamorphism. They are mechanical mixtures of components that primarily formed in the solar nebula but include small amounts of unprocessed presolar material. Chemically they are similar to the nonvolatile (i.e., excluding H, noble gases, C, N, and O) composition of the Sun. However, chondrites do vary enough in bulk composition for them to have been subdivided into five classes; the three principal ones being the ordinary, carbonaceous, and enstatite chondrites. These classes are divided into numerous subgroups. One of these, the CI carbonaceous chondrites, is almost indistinguishable from the measured nonvolatile solar photosphere composition.

The most abundant components (50 to 80% by volume) in chondrites are chondrules (17)—mm-sized, silicate/metal spheres. Only the CI carbonaceous chondrites lack chondrules. Chondrules formed as molten droplets in the solar nebula by flash heating to 1700 to 2100 K and rapid cooling (10 to

1000 K per hour). The size distributions, compositions, and proportions of different types of chondrules all vary between chondrite groups. There is also evidence that chondrule material was recycled, suggesting multiple formation events.

The abundance of chondrules in chondrites indicates that they were produced by one of the most important (at least in the asteroid belt) solar nebular processes, but their origin remains enigmatic. The variations in their properties between chondrite groups and the evidence for recycling has lead to a generally held view that they formed by localized phenomena throughout the asteroid belt (17). At present, the two most promising localized heat sources are shock waves and massive lightning discharges (18).

A different hypothesis (19) suggests that chondrules formed when dust aggregates were entrained and heated in bipolar jets (also called x-wind) near (~0.06 AU) the Sun. Accelerated into ballistic trajectories, the chondrules would then have fallen back throughout the solar nebula and not just at 2 to 3 AU. At present, there is no evidence that requires a jet model, and, as with all other models, it is unclear whether it can explain all the variations in chondrule properties within and between the chondrite groups. If chondrules did form in an x-wind, their abundance



Fig. 1. The time objects of various sizes take to drift into the Sun though gas drag as a function of the radial distance *r*, in AU from the Sun, that they start from [after (52)]. The lines are marked with the radii of the objects (S), in centimeters, that were used to calculate them. The calculations do not include the overall drift of the inner solar nebula gas toward the Sun, so they are upper limits for the time scales of loss to the Sun. The *y* axis shows the characteristic lifetime τ_c . $P \propto r^{-3}$, T = (600/r) K, and $\rho_s = 3$ g/cm³.

 Table 1. Summary of the stages in the formation of a Sunlike star [see (50) and references therein]. pd, poorly determined.

Stage	Lifetime (years)	Disk mass (M _o)	Accretion rate (M _☉ /year)	Fraction with jets
	М	IC core collapse		
Ouiescent	~10 ⁶ –10 ⁷	,		
Triggered	~10 ⁵			
50		Class 0		
Protostar + disk	~104	pd	~10 ⁻⁵	~1
		Class I		
Protostar + disk	~10⁵	pd	$2-5 imes 10^{-6}$	≥0.6
Quiescent	~10 ³ –10 ⁴	I	~10 ⁻⁷	
FU Orionis outburst				
	$\sim 10^2$		$\sim 10^{-4}$	
		Class II		
Classic T Tauri + disk	10⁵–10 ⁷	0.001-1	10 ⁻⁶ -10 ⁻¹⁰	~0.1
		Class III		
Weak-line T Tauri		0	0	0



Fig. 2. (A) The CI chondrite normalized elemental abundances in bulk carbonaceous (CM, CO, and CV) and ordinary chondrites (OC) (53) versus their 50% condensation temperatures (54). The correlation between abundance and condensation temperature (volatility) is striking. The elements are divided into refractory (>1350 K), moderately volatile (700 to 1350 K), and highly volatile (<700 K). The common elements (Mg, Si, and Fe) have been included with the moderately volatile elements to simplify the plot. The three ordinary chondrite groups have been combined, also to simplify the plot. (B) The CI and rim/matrix normalized abundances of the highly volatile and moderately volatile elements. The rim/matrix abundances used are from (24) and are given in the key. (C) The CI normalized moderately volatile and refractory element abundances after subtraction of a CI-like rim/matrix component (see key) and correcting totals back to 100%.

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in chondrites implies that 50 to 80% of the condensable material in the asteroid belt, and probably other regions of the inner solar system, was processed through the bipolar jets. Presumably there would be substantial consequences for the evolution of the asteroid belt if this much solid material was being added to it.

Minor but important constituents of chondrites are µm- to cm-diameter calcium-aluminum-rich inclusions (CAIs) (20). They are the oldest known solar system objects preserved in meteorites. CAIs formed at high temperatures (1700 to 2400 K), although not all were molten when they formed and most probably experienced more prolonged heating and cooling than chondrules. Like chondrules, some CAIs seem to have experienced multiple heating events. Most exhibit elemental or isotopic evidence that they or their precursors formed by evaporation and/or condensation. Also, the sizes, abundances, and proportions of different types of CAI vary between chondrite groups.

The origin of CAIs is shrouded in even more mystery than that of chondrules. The variability of CAI properties and abundances between chondrite groups is consistent with localized formation in the asteroid belt. However, almost all unaltered CAIs have similar ages and similar systematic variations in their O isotopes. These observations require that if they did not all form in the same place, then at the very least they formed by a common process over a limited period of time early in solar system history. Formation in bipolar jets is a possibility (19). Their age indicates that they would have formed when jets were present, but, as with chondrules, there is no evidence that requires jets as the heat sources.

Chondrules and CAIs are often surrounded by fine-grained rims. In some cases, chondrules accreted their rims while they were still hot and plastic. This assemblage is then cemented together by a fine-grained matrix. The rims and matrix (hereafter rim/matrix) are relatively rich in volatile species, such as Na, Cl, and water. They also contain organic matter (up to 2 weight %), which probably formed in the presolar molecular cloud (21), and small abundances of various types of presolar grains that formed in circumstellar environments (22).

Bulk chemistry—evidence for global or local heating? Because material accreting onto the solar nebula would initially have had a solar/CI-like composition, variations in chondrite chemistry are generally modeled in terms of fractionations relative to a CI-like starting material. Astrophysical predictions of initially high inner solar nebula temperatures combined with the observation that most elemental fractionations in chondrites are related to volatility in some way led to the picture of an entirely vaporized inner solar nebula. Subsequently, as the inner solar nebula cooled, solids would have condensed from the gas in a thermodynamically predictable sequence (Fig. 2).

The variations in refractory element abundances are consistent with enrichments (carbonaceous chondrites) or depletions (ordinary and enstatite chondrites) of CAI-like material and forsterite (Mg_2SiO_4) (23) (Fig. 2). The abundances of CAIs in chondrites are qualitatively consistent with the enrichments and depletions inferred from their bulk chemistry. However, here we concentrate on the fractionations of the moderately and highly volatile elements because they hold the most promise for constraining conditions before and during chondrite formation.

Normalization of elemental abundances to rim/matrix abundances (Fig. 2B) indicates that highly volatile element concentrations in rim/matrix are similar ($\sim 1.2 \times CI$) in carbonaceous and ordinary chondrites. Some of the scatter in Fig. 2B may reflect analytical/sampling errors and modification by parent body processes. A similar normalization of presolar grain and organic matter abundances also produces CI-like concentrations (21, 24). Both the highly volatile elements and the presolar material seem to be associated in a component of rim/matrix that escaped high temperatures in the solar nebula. The bulk compositions of the rim/matrix material vary between these chondrite groups, and none are identical to CIs. Consequently, highly volatile elements and presolar matter abundances in this primitive component must be somewhat greater than in CIs. Perhaps CIs contained \sim 20% chondrules but the evidence for them has been erased by the extensive aqueous alteration they have experienced. The absence of systematic fractionations in Fig. 2B indicates that these chondrites were assembled when solar nebular temperatures were <400 K, i.e., in the T Tauri phase. In fact, members of most carbonaceous and ordinary chondrite groups have experienced aqueous alteration, suggesting that ambient temperatures were low enough for some water-ice to condense. Formation of hydrous silicates in the solar nebula, an alternative source of water, is kinetically inhibited (25).

After subtraction of a CI-like rim/matrix component, the remaining moderately volatile elements in the carbonaceous and ordinary chondrites exhibit similar behaviors (Fig. 2C). There are variations in some elements between chondrite groups. Nevertheless, it is plausible that a similar mechanism, which has yet to be definitively identified, was responsible for the moderately volatile element fractionations in all these meteorites. The long-standing debate has been whether this mechanism was associated with chondrule formation (26) or nebular condensation (27).

Volatility-dependent fractionations could occur in a cooling inner solar nebula ($T \leq$

1300 K) if condensates coagulate and decouple from the sunward-migrating gas (27). This process can reproduce the moderately volatile element patterns, provided that initially the disk mass was >0.15 M_{\odot} and mass accretion rates were high (>10⁻⁷ M_{\odot} /year) (28). Thus, meteorites may preserve in their bulk compositions a record of solar nebular conditions beginning in the class 0-I phases of YSO evolution. However, cooling from 1300 to 600 K takes several tens of thousands of years. To prevent the condensates from drifting into the Sun (Fig. 1), they must be preserved in at least km-sized objects. These must later be disrupted before chondrule formation and thoroughly reprocessed before the final assembly of the chondrites because the condensates have not survived.

If condensation fractionation was a more local process (e.g., chondrule formation), time scales could have been shorter and preservation of the fractionated material less problematic, although a number of objections will need to be overcome (29). One of these is that the elemental fractionations must be accomplished without substantial isotopic fractionation (30). To produce the elemental fractionations, there must be some evaporation from the chondrules. Evaporation is often accompanied by large isotopic fractionations. In chondrules, elements such as K and Fe do show considerable variations in their abundances without exhibiting any evidence for isotopic fractionation (31). One explanation for this is that during formation, they approached equilibrium with the solar nebula gas, in which case fractional recondensation could have occurred during cooling. Evaporated material will partially recondense onto dust that is present. Fractionation of chondrules from dust and gas, as well as silicates from metal, is likely to be a natural process in the solar nebula (11). Thus, although fractionation in a cooling nebula is the generally favored mechanism for producing moderately volatile element abundances, fractionation during chondrule formation should not be ruled out. Finally, if chondrules formed in bipolar outflows, the abundance of moderately volatile elements in them would indicate modest ambient solar nebula temperatures $(\leq 700 \text{ K})$ close to the Sun, which may be difficult even in the context of T Tauri disks. Also, bipolar outflows are uncommon in T Tauri stars (Table 1).

Radioactivities in the Solar System

Short- and long-lived radionuclides were present when the solar system formed (Table 2). The long-lived nuclides are now the principal heat sources in the terrestrial planets and are some of the most important geochemical tools for identifying processes and time scales on Earth and in meteorites. The now extinct short-lived nuclides provide constraints for time scales of solar system formation and early evolution, as well as being potential heat sources responsible for the metamorphism and melting many asteroids experienced.

Short-lived radionuclides—triggered collapse or local synthesis? The presence of the short-lived ⁴¹Ca and ²⁶Al in meteorites requires either (i) that the collapse of the presolar molecular cloud core was triggered by a stellar wind (otherwise collapse occurs on time scales that are much longer than their half-lives) or (ii) that these nuclides were synthesized in the solar system by energetic particles after collapse began (32). To date, attempts to model the abundances of all the short-lived nuclides by particle irradiation have failed. Numerical simulations show that fairly typical 10 to 50 km/s shock waves can trigger core collapse and there is observational evidence for triggered star formation (33). The most likely sources of these shock waves are supernovae, Wolf-Ravet stars, or asymptotic giant branch stars. The driving gas that produces the shock waves from any of these stars will carry with it freshly synthesized short-lived nuclides. The total time from synthesis to injection into the collapsing solar system may be ~ 2 to 4×10^5 years (34), consistent with the half-lives of the shortest lived radionuclides.

About 10% by mass of the material associated with a shock wave encountering the protosolar core will ultimately be injected into it, but the fraction injected will vary considerably with time and position (35). Whether mixing in the disk can erase these heterogeneities is unknown. There is some indication for a radial zonation of ⁵³Mn (36, 37), but the most dramatic evidence for solar nebula heterogeneity is found in oxygen. Oxygen exhibits mass-independent isotopic variations in objects that range in size from a few um across to planets. The original explanation for this was that ¹⁶O-rich supernova material was heterogeneously distributed throughout the solar nebula (38). However, the absence of correlated isotopic anomalies

in any other element or direct evidence for this supernova material despite preservation of other presolar materials has led to speculation that the mass-independent isotopic effects have a chemical rather than nucleosynthetic origin (39). None of the three proposed stellar sources are able to explain the abundances of all the short-lived radionuclides, particularly ¹⁰Be, which is produced by particle irradiation rather than stellar nucleosynthesis (Table 2). At present, a hybrid model best explains the short-lived radioactivities (32)-most radioactivities are derived by shock wave injection, whereas ¹⁰Be and possibly ⁵³Mn are produced in the solar system by particle irradiation.

Time scales. For a short-lived radionuclide to be useful as a chronometer, its initial relative abundance (Table 2) must have been uniform throughout the solar nebula. This may not be the case in the shock wave injection and hybrid models. Also, the short-lived nuclides can only give relative time scales. To get absolute time scales, the short-lived nuclide time scales must be coupled to precise absolute ages determined with the U-Pb system. Consistency among all chronometers would indicate an initially uniform solar nebula. The determination of precise absolute and relative time scales is a difficult task, but most evidence favors a fairly homogeneous solar nebula (40).

Most unaltered CAIs have the highest initial abundances of ¹⁰Be, ²⁶Al, ⁴¹Ca, and ⁵³Mn of any measured solar system objects. They also have the oldest measured absolute ages of 4566 \pm 2 million years ago (Ma) (41). Their initial isotopic ratios (Table 2) are therefore assumed to be representative of the earliest solar system. However, there are some CAIs that contain stable isotope nuclear anomalies indicative of excesses or depletions of presolar components relative to solar. Surprisingly, most of these unusual CAIs retain no evidence of short-lived radioactivities, perhaps because they formed before the injection of much newly synthesized material accompanying the shock wave.

Table 2. The short-lived radionuclides known to have been present in the early solar system, their half-lives, abundances, and possible sources [after (32, 51), and references therein].

Parent nuclide	Daughter nuclide	Half-life (Ma)	Initial abundances	Potential sources*
⁴¹ Ca	⁴¹ K	0.1	41 Ca/ 40 Ca $\approx 1.5 \times 10^{-8}$	SN, AGB, WR, EPI
²⁶ Al	²⁶ Mg	0.7	26 Al/ 27 Al $\approx 5 \times 10^{-5}$	SN, N, AGB, WR, EPI
⁶⁰ Fe	⁶⁰ Ni	1.5	60 Fe/ 56 Fe $\approx 2 \times 10^{-8}$	SN, AGB
¹⁰ Be	¹⁰ B	1.5	10 Be/ 9 Be \approx 9 $ imes$ 10 $^{-4}$	EPI
⁵³ Mn	⁵³ Cr	3.7	53 Mn/ 55 Mn $pprox$ 0.9–4.4 $ imes$ 10 $^{-5}$	SN, EPI
¹⁰⁷ Pd	¹⁰⁷ Ag	6.5	107 Pd/ 108 Pd \approx 4.5 $ imes$ 10 $^{-5}$	SN, AGB, WR
¹⁸² Hf	¹⁸² W	9	$^{182}\text{Hf}/^{180}\text{Hf} \approx 2 \times 10^{-4}$	SN
129	¹²⁹ Xe	15.7	$(129)/(127) \approx 1 \times 10^{-4}$	SN
²⁴⁴ Pu	α, SF†	82	244 Pu/ 238 U \approx 7 \times 10 $^{-3}$	SN

*SN, supernova; N, nova; AGB, asymptotic giant branch; WR, Wolf-Rayet; EPI, energetic particle irradiation. †SF, spontaneous fission products. Chondrule ages based on 26 Al range from -0.7 to >5 Ma after CAIs (42). This may reflect a real range in formation ages, but there is evidence for alteration and/or meta-morphism in all the meteorites studied. If, as seems likely, the Al-Mg systems in many of the chondrules were disturbed by these secondary processes, the oldest ages are probably closest to the actual formation ages. Even if chondrules are only 1 to 2 Ma younger than CAIs, this would place chondrule and chondrite formation in the T Tauri stage of YSO evolution. Preservation of CAIs for this length of time without losing them to the Sun is a considerable problem.

The formation ages of the chondrites are poorly known. The oldest measured chondrite, the ordinary chondrite Ste. Marguerite (H4), has an absolute age of 4563 \pm 1 Ma (43), an Al-Mg age of 5.6 \pm 0.4 Ma after CAls (44), and a Hf-W age of 4 ± 2 Ma (45). These are probably metamorphic closure ages for the dated minerals and are, therefore, minimum ages for the formation of the Hgroup ordinary chondrite parent body. The magmatic meteorites (the stony achondrites and the stony-iron and the iron meteorites), produced during melting and differentiation, provide useful limits for the formation ages of their parent asteroids. The oldest absolute crystallization age of any achondrite is 4558 ± 1 Ma (46). However, ⁵³Mn data suggest that the parent body of the so-called HED (howardite-eucrite-diogenite) meteorite association, probably the asteroid 4 Vesta (~550 km across), underwent differentiation and core formation at 4564.8 \pm 0.9 Ma, within 0 to 4 Ma of CAI formation (36). Hf-W dating of iron meteorites also points to rapid differentiation of their parent bodies $(\leq 5 \text{ to } 15 \text{ Ma after CAIs})$ (45). The age limits set by these different meteorites are all consistent with model predictions that it would take $\sim 10^5$ to 10^6 years to make km-sized to embryo-sized objects, respectively, in the asteroid belt.

Dating the time of formation of Earth, the Moon, and Mars, the only planetary objects we have samples of, has proven difficult because of their prolonged evolution. Hf-W data suggest that the formation of the Moon in a giant impact and the isolation of Earth's core from the silicate mantle both occurred -50 ± 10 Ma after solar system formation (45). Mars' core became isolated from its mantle within ~ 30 Ma of solar system formation (47). Isolation of a planet's core probably marks the last major accretion event, and these time scales are consistent with model estimates of $\sim 10^8$ years to form the terrestrial planets. Mars is not much larger than an embryo. so it is not surprising that its accretion ended before Earth's. Because core formation on planetesimals occurred within 5 to 15 Ma of solar system formation, the terrestrial planets would have formed from already differentiated bodies. This must be taken into account when modeling planetary accretion and its geochemical consequences.

Retention of a primitive atmosphere on Earth began at about 4460 \pm 20 Ma on the basis of the abundances of radioactively produced ⁴⁰Ar and ¹²⁹Xe (41). Again this probably marks the end of major impact events that would have removed much of any preexisting atmosphere. These impacts could have been smaller than ones required to reequilibrate the mantle and core. Interestingly, there is evidence that Earth already had a continental crust and oceans by 4300 to 4400 Ma (48). Because retention of Earth's atmosphere occurred after dissipation of the disk, Earth probably did not accrete most of its water from comets. Cometary water is very D-rich, requiring an admixture of D-poor solar nebula hydrogen to reproduce Earth's D/H ratio. Water-bearing asteroids and/or icy planetesimals that formed near Jupiter are more likely sources (49).

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