Chronology of Asteroid Accretion and Differentiation

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The study of short-lived, now extinct radionuclides offers constraints on the duration of planetesimal formation and on other processes and events, which took place in the early solar system. The relative chronometers based on the decay of ^{53}Mn to ^{53}Cr ($T_{1/2}$ = 3.7 m.y.) and of ^{26}Al to ^{26}Mg ($T_{1/2}$ = 0.73 m.y.) provide an adequate time resolution of at least 1 m.y. A calibration of these relative chronometers with an absolute Pb-Pb chronometer permits converting relative ages into absolute ages. Using reasonable assumptions, an absolute timescale for events in the early solar system can be constructed. Based on the studies of these isotope systems in various meteorites, we estimated the formation time of the first high-temperature condensates (Ca-Al-rich meteorite inclusions) in the solar system, inferred constraints on the duration of planetesimal accretion, calculated the time of planetary melting, mantle, and core formation, and constrained the timing of igneous processes and thermal metamorphism within planetesimals.

1. INTRODUCTION

The main topic of this chapter is the discussion of the timing of asteroid accretion, differentiation, and interior thermal processes. These issues are closely related to a more general subject: the reconstruction of a timescale for various processes and events in the early solar system. We will not discuss theoretical chronological constraints obtained with the use of dynamical models (e.g., *Weidenschilling,* 2000). Instead, we will focus on the constraints for asteroid formation and evolution that are provided by radioactive clocks — the isotopic chronometers based on the radioactive decay of various nuclides.

It has been known for several decades that the age of the solar system is approximately 4.55–4.57 b.y. (e.g., *Patterson,* 1956; *Tatsumoto et al.,* 1976; *Chen and Tilton,* 1976). At present, however, it is possible to determine ages of solar system materials with much higher precision. Newly developed isotopic chronometers permit a time resolution approaching 1 m.y. or even better. The development of techniques to define high-resolution timescales is crucial for understanding the processes that occurred during the very early stages of solar system evolution.

The results that we will discuss below are based on the experimental study of meteorites — the fragments of asteroids that are transported from the asteroid belt to the Earth due to asteroid collisions in space. The wide variety of meteorite classes found on Earth implies a broad diversity of asteroid types. We do not know how many asteroid parent bodies we actually sample with the meteorites in our collections. Nevertheless, this number must be large, and, according to some estimates, may be as high as >135 (*Meibom and Clark,* 1999).

The objective here is to briefly describe some recent chronological results obtained in laboratory meteorite studies and to relate them to the main question we are addressing: How old are the asteroids?

2. ISOTOPIC CHRONOMETERS

The isotope chronometers based on the radioactive decay of the long-lived radionuclides are well known and have been in use for several decades. They include Rb-Sr, Sm-Nd, U-Pb, Re-Os, K-Ar, and some other chronometers. The half-lives of the parent nuclides are billions to tens of billions of years, e.g.,

$$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr}\ (T_{1/2} \approx 4.9 \times 10^{10}\ \mathrm{yr})$$

$$^{147}\mathrm{Sm} \rightarrow {}^{143}\mathrm{Nd}\ (T_{1/2} \approx 1.1 \times 10^{11}\ \mathrm{yr})$$

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb}\ (T_{1/2} \approx 4.5 \times 10^{9}\ \mathrm{yr})$$

$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb}\ (T_{1/2} \approx 0.7 \times 10^{9}\ \mathrm{yr})$$

The principles and use of these isotopic systems in geochronology and cosmochronology are described in detail elsewhere (e.g., see *Dickin,* 1995) and will not be repeated here.

The important requirements for dating early events in the solar system are that these chronometers should provide an adequate time resolution and should be insensitive to late secondary events (such as a late bombardment of an asteroid's surface). At the present state of technology only the U-Pb chronometer can provide an adequate time resolution of ~1 m.y. (e.g., *Lugmair and Galer,* 1992; *Göpel et al.,* 1994). However, the drawback of this system is that in many cases it was disturbed by natural phenomena such as shock or reheating, which can compromise the age information obtained with this method (e.g., *Carlson and Lugmair,* 2000). The Sm-Nd-isotopic system appears to be more robust, although the uncertainties in the Sm-Nd ages are usually not less than ~25 m.y. and, thus, a high-resolution timescale cannot be constructed with this chronometer.

The other type of chronometers is based on relatively short-lived nuclides. There is a series of short-lived radioactive nuclides with lifetimes on the order of a million to a hundred million years. These lifetimes are long enough to survive the interval between their production and the formation of solids in the solar system, but are still comparatively short, so that these nuclides are practically fully decayed and now extinct in the solar system. The presence of short-lived radionuclides in the early solar system may be due either to nucleosynthetic production within stars and subsequent rapid transport to and injection into the nascent solar system (e.g., *Cameron et al.,* 1997; *Boss and Vanhala,* 2000) or, possibly, to local production by high-energy particles from the Sun (e.g., *Clayton and Jin,* 1995; *Shu et al.,* 1997). The study of these now-extinct radionuclides in meteorites has offered reliable constraints on the time and duration of the formation of solid bodies in the early solar system. The former presence in meteorites of more than ten short-lived radionuclides has been discovered so far (see the recent review by *Podosek and Nichols,* 1997). Several examples are

$$^{41}\mathrm{Ca} \rightarrow {}^{41}\mathrm{K}\ (T_{1/2} = 0.10\ \mathrm{m.y.})$$

$$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}\ (T_{1/2} = 0.73\ \mathrm{m.y.})$$

$$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B}\ (T_{1/2} = 1.5\ \mathrm{m.y.})$$

$$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Ni}\ (T_{1/2} = 1.5\ \mathrm{m.y.})$$

$$^{53}\mathrm{Mn} \rightarrow {}^{53}\mathrm{Cr}\ (T_{1/2} = 3.7\ \mathrm{m.y.})$$

$$^{129}\mathrm{I} \rightarrow {}^{129}\mathrm{Xe}\ (T_{1/2} = 17\ \mathrm{m.y.})$$

$$^{146}\mathrm{Sm} \rightarrow {}^{142}\mathrm{Nd}\ (T_{1/2} = 103\ \mathrm{m.y.})$$

The importance of these radionuclides is that due to their short half-lives, they could serve as very sensitive chronometers for events in the early solar system and as tracers for early planetary evolution. Together with longer-lived radionuclides the abundances of these short-lived species provide constraints on nucleosynthetic timescales and models of nucleosynthesis. The short-lived nuclide ^{26}Al is of special importance. It is considered as a viable heat source for early heating of planetesimals and, in some cases, for their differentiation (see *McSween et al.,* 2002).

The former presence of an extinct radionuclide is revealed in the form of isotopic anomalies in the daughter element. Obviously, a daughter element should have at least two isotopes so that the anomaly can be observed in principle. In addition, since the abundances of these radionuclides are usually small, it is often necessary to study objects with a high parent-to-daughter element ratio. In this case, even a small addition of the radiogenic daughter nuclide will result in a measurable shift in the isotopic composition of the daughter nuclide.

One of these radionuclides, ^{53}Mn, with a half-life of 3.7 m.y., is especially suitable for high-resolution chronological studies of the first ~20 m.y. of solar system history. The former presence of ^{53}Mn is indicated by excesses relative to the terrestrial "standard" value of the daughter nucleus, ^{53}Cr. One of the advantages of the ^{53}Mn-^{53}Cr chronometer is that Mn and Cr are abundant elements in solar system materials and that the ^{53}Mn-^{53}Cr system, therefore, is potentially useful for dating a wide variety of ancient objects. Another advantage is the presence in many objects of a Cr-spinel phase which has a very low Mn/Cr ratio. This permits high-precision measurements of initial ^{53}Cr/^{52}Cr ratios for the time of isotopic closure of the Mn-Cr system. After the pioneering finding of the vestiges of ^{53}Mn in Allende refractory inclusions (*Birck and Allègre,* 1985), excesses of ^{53}Cr were detected in various solar system objects: carbonaceous chondrites, enstatite chondrites, ordinary chondrites, pallasites, iron meteorites, angrites, eucrites, mesosiderites, SNC meteorites, and primitive achondrites (see references in *Lugmair and Shukolyukov,* 1998). In many cases, the measured relative ^{53}Cr/^{52}Cr excesses in mineral phases of these meteorites are correlated with their respective Mn/Cr ratios, which indicates *in situ* decay of ^{53}Mn. From the slope of the correlation line of measured ^{53}Cr/^{52}Cr vs. ^{55}Mn/^{52}Cr data pairs a relative abundance of ^{53}Mn (that is the ^{53}Mn/^{55}Mn ratio) at the time of isotopic closure can be obtained. The relative ages of two meteorites, 1 and 2, are then calculated from their ^{53}Mn/^{55}Mn ratios

$$\Delta T_{1-2} = 1/\lambda \ \ln[(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_1/(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_2] \qquad (1)$$

where λ is the decay constant of ^{53}Mn.

Using this and other short-lived radionuclides, we can date processes that occurred 4.56 b.y. ago with a resolution of 1 m.y. or better. However, these chronometers have a disadvantage: Because the parent nuclides are extinct, only relative ages can be obtained. Thus we need to map these relative ages onto an absolute timescale.

3. MAPPING OF THE RELATIVE CHRONOMETERS ONTO AN ABSOLUTE TIMESCALE

Figure 1 shows an example of such a procedure. The graph illustrates our results for the Mn-Cr-isotopic system in a differentiated meteorite, the angrite LEW 86010 (*Lugmair and Shukolyukov,* 1998). This meteorite is an ideal sample for calibration purposes. The angrites are early equilibrated planetary differentiates that cooled fast, do not show any signs of later disturbance, and have absolute ages that are precisely known. The Pb-Pb age of LEW 86010 is 4557.8 ± 0.5 Ma (*Lugmair and Galer,* 1992). In addition, in LEW

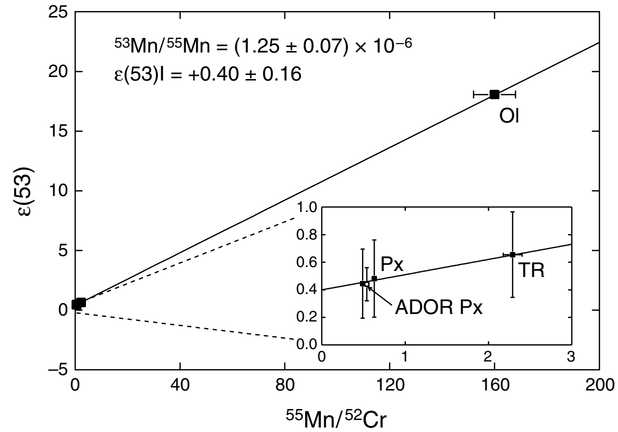

Fig. 1. Manganese-53–chromium-53 systematics in the angrite LEW 86010 (LEW). Here and in the following figures the y-axis represents the deviations of the measured $^{53}Cr/^{52}Cr$ ratios relative to the standard terrestrial value. These deviations are expressed in ε units (1 part in 10^4). TR = total rock, Px = pyroxene, Ol = olivine. The slope of the best-fit line yields the $^{53}Mn/^{55}Mn$ ratio at the time of isotopic closure. The precise absolute age of LEW (*Lugmair and Galer,* 1992) and the obtained $^{53}Mn/^{55}Mn$ ratio allow the relative Mn-Cr chronometer to be mapped onto an absolute timescale. The insert shows enlarged the results for the mineral phases with small Mn/Cr ratios. The data point for a pyroxene separate from the angrite Angra dos Reis (ADOR Px) is shown for comparison. It is totally consistent with the LEW data that reflects a contemporaneous formation of these two angrites (*Lugmair and Galer,* 1992). ε(53)I is the initial $^{53}Cr/^{52}Cr$ ratio at the time of isotopic closure.

86010 the range of the $^{55}Mn/^{52}Cr$ ratios is rather large — from ~0.5 in pyroxenes up to ~160 in olivines — allowing for the precise determination of the $^{53}Mn/^{55}Mn$ ratio at the time of isotopic closure. The y-axis in Fig. 1 represents the relative abundance of ^{53}Cr ($^{53}Cr/^{52}Cr$) with respect to the terrestrial Cr composition, expressed in ε units (1ε is 1 part in 10^4, or 0.01%). The x-axis is the $^{55}Mn/^{52}Cr$ ratio. The $^{53}Cr/^{52}Cr$ ratios in the mineral phases are correlated with the respective $^{55}Mn/^{52}Cr$ ratios. The slope of this line yields the relative abundance of extinct ^{53}Mn at the time this meteorite formed. The fact that the angrites cooled fast (*Störzer and Pellas,* 1977) suggests that both the U-Pb and the Mn-Cr isotope systems closed approximately at the same time or, more correctly, within the timespan provided by the time resolution of our isotopic chronometers. Thus, the obtained value of (1.25 ± 0.07) × 10^{-6} represents the $^{53}Mn/^{55}Mn$ ratio at 4557.8 Ma. This data pair now make it possible to map the relative ^{53}Mn-^{53}Cr chronometer, that is the relative Mn-Cr ages obtained for other meteorite samples, onto an absolute timescale.

A necessary condition for this method to yield valid absolute ages is that both the material of the absolute time marker and that of the meteorite to be dated come from an isotopically uniform reservoir. The isotopic studies of various solar system bodies have shown that the solar nebula has been well mixed: The isotopic compositions of elements are essentially the same in all studied objects. There are a few exceptions, but these anomalies are confined to a limited number of objects and do not play a significant role on a large planetary scale. The isotopic homogeneity of the solar system material is a result of the prolonged and thorough mixing of numerous nucleosynthetic components of various origins that were part of the solar nebula. However, the short-lived radionuclides were injected into or formed within the solar nebula just prior to or during solar system formation. During the course of a few 10^5 to 10^6 yr, this material may not have been distributed homogeneously within the solar system.

We have shown recently that the relative ^{53}Cr abundance in the Earth-Moon system, the martian meteorites, and the "asteroid belt" meteorites is a function of their present heliocentric distance (*Lugmair and Shukolyukov,* 1998). This led us to suggest that the observed radial gradient in the relative ^{53}Cr abundance may be due to an original radially heterogeneous ^{53}Mn distribution. The alternative explanation is an early, volatility-driven, Mn/Cr fractionation in the nebula with an originally homogeneous ^{53}Mn distribution (e.g., see *Cassen and Woolum,* 1997). The discussion of the details of these scenarios (*Lugmair and Shukolyukov,* 1998; *Shukolyukov and Lugmair,* 2000a), however, is beyond the scope of this chapter. What is important in the present context is that no detectable variations of the $^{53}Cr/^{52}Cr$ ratios were found among the studied bulk asteroid belt bodies (*Shukolyukov and Lugmair,* 2000a). This, therefore, implies that the original ^{53}Mn abundance was essentially the same among these objects. Thus, the ^{53}Mn-^{53}Cr system can be used as a chronometer, at least for samples from the asteroid belt.

4. ABSOLUTE TIMESCALES FOR EVENTS IN THE EARLY SOLAR SYSTEM

4.1. Refractory Inclusions, Chondrules, and Planetesimals

Among all early solar system objects dated in the past, Ca-Al-rich inclusions (CAIs) provided the oldest high-precision absolute ages. These refractory inclusions (see *MacPherson et al.,* 1988, for a review on CAI mineralogy and models of formation) are considered the first condensates of matter in the solar system. An average absolute Pb-Pb age of several CAIs from the Allende chondrite is 4566 ± 2 Ma (*Göpel et al.,* 1991). This age is often taken to be the best estimate for the solar system age. However, one cannot exclude the possibility that this CAI age reflects processes of alteration or late isotopic reequilibration rather than the true formation age. If so, this value would only be a lower limit for the true time of CAI formation.

Additional constraints for the solar system age can be derived from the ^{53}Mn-^{53}Cr system. Among planetary samples, the terrestrial $^{53}Cr/^{52}Cr$ value is the lowest known so far. The lower $^{53}Cr/^{52}Cr$ ratios (by ~1ε) found in CAIs from carbonaceous chondrites (*Birck and Allègre,*1985; *Nyquist et al.,* 2001) most likely do not represent bulk solar system material. Indeed, CAIs contain not only the vestiges of some ^{53}Mn decay but also exhibit pronounced anomalies in other isotopes of Cr (*Papanastassiou,* 1986; *Rotaru et al.,* 1992; *Podosek et al.,* 1997). This indicates that the measured ^{53}Cr/^{52}Cr ratios in CAIs reflect a complex superposition of the ^{53}Mn decay process and mixing of at least two Cr components (possibly of presolar origin) with anomalous isotopic composition. We believe, therefore, that the chronological meaning of the initial ^{53}Cr/^{52}Cr ratios in CAIs is rather tenuous. Thus, we use the terrestrial ^{53}Cr/^{52}Cr ratio, defined as 0ε, as the upper limit for the solar system initial value (SSI). Using the Mn-Cr data obtained for the HED (howardite-eucrite-diogenite) parent body (see Fig. 2 and the next section for details), with an initial ^{53}Cr/^{52}Cr ratio of +0.25ε and a chondritic ^{55}Mn/^{52}Cr ratio of 0.76, we estimated a minimum solar system age of ~4568 Ma (*Lugmair and Shukolyukov,* 1998). This value is still in agreement with the above mentioned CAI Pb-Pb age of 4566 ± 2 Ma. Using a similar approach and SSI = –0.42ε, as derived from an extrapolation of the previously discussed ^{53}Cr/^{52}Cr gradient to zero heliocentric distance, one can obtain an estimate for an upper limit of the solar system age of ~4571 Ma (*Lugmair and Shukolyukov,* 1998, 2001). Thus, these estimates for the age of the solar system provide a rather narrow range of only about 3 m.y. It has to be noted that estimates of the "solar system age" based on short-lived radioactive nuclides require that these nuclei were either injected into or produced within the nebula itself within a timespan after T_0, which is short relative to their respective half-lives.

A recent study of the Mn-Cr isotopic system in carbonates from the Kaidun carbonaceous chondrite (*Hutcheon et al.,* 1999) provides further constraints. These results indicate that the ^{53}Mn/^{55}Mn ratio at the time when these carbonates formed was ~9.4×10^{-6}. Using this value and the angrite LEW 86010 as a time marker yields a time for this event of ~4569 Ma. Clearly, carbonate formation in a meteorite parent body can only occur after the formation of the first solids. Hence, a time of ~4569 Ma can only be a lower limit for the solar system age, making ~4571 Ma a more reasonable age estimate. This also strongly suggests that the lower Pb-Pb age obtained for CAIs most likely is a result of later alteration.

Additional constraints can be obtained from the ^{26}Al-^{26}Mg chronometer. The majority of CAIs are characterized by a "canonical" initial ^{26}Al/^{27}Al ratio of ~5×10^{-5} (see *MacPherson et al.,* 1995, for a review). This sharp clustering implies that the inclusions formed within an interval of less than 1 m.y. The comparison of this "canonical" value with the ^{26}Al data from feldspars in the H4 chondrite Ste. Marguerite [$(2.0 \pm 0.6) \times 10^{-7}$ (*Zinner and Göpel,* 1992)] yields a time difference between the isotopic closure of the ^{26}Al-^{26}Mg system in Ste. Marguerite and CAIs of 5.6 m.y. Using the Pb-Pb age of phosphates, 4562.7 ± 0.6 Ma (*Göpel et al.,* 1994) gives an absolute age for CAIs of ~4568 Ma. If, however, the feldspars in Ste. Marguerite predate the

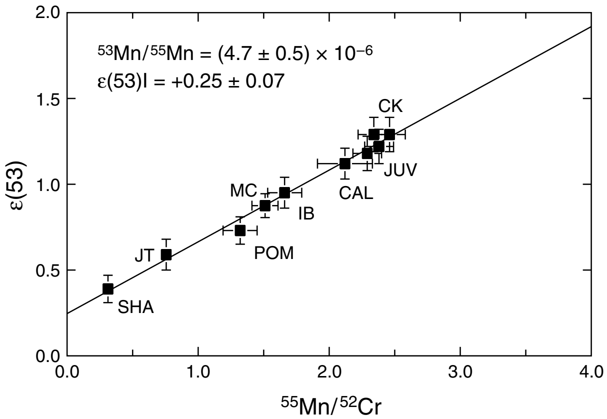

Fig. 2. Manganese-53–chromium-53 systematics in the HED parent body. The measured ^{53}Cr/^{52}Cr ratios for bulk meteorites are plotted vs. their respective ^{55}Mn/^{52}Cr ratios (data from *Lugmair and Shukolyukov,* 1998). The samples include two diogenites [Johnstown (JT) and Shalka (SHA)] and six noncumulate eucrites [Chervony Kut (CK), Juvinas (JUV), Caldera (CAL), Ibitira (IB), Pomozdino (POM), and the cumulate eucrite Moore County (MC)]. The data points form a well-defined isochron whose slope corresponds to the ^{53}Mn/^{55}Mn ratio of $(4.7 \pm 0.5) \times 10^{-6}$, which dates the global differentiation of the HED parent body at 4564.8 ± 0.9 Ma (see text).

phosphates by 3–4 m.y., as suggested by their I-Xe age of ~4566 Ma (*Brazzle et al.,* 1999; *Gilmour,* 2000) and the recently obtained metamorphic ^{53}Mn-^{53}Cr age of 4565 ± 0.7 Ma (*Polnau and Lugmair,* 2001), then the CAI age would be close to 4571 Ma.

In summary, a time of ~4571 Ma is our current "best estimate" for the solar system age. This age estimate of ~4571 Ma would then mark the time when the first high-temperature condensates (CAIs) were starting to form. Considering the recently measured variation of ^{26}Al/^{27}Al between petrographically distinct components within the same Allende CAI (*Hsu et al.,* 2000), it appears that CAI formation may have persisted for several 10^5 yr. The relative ^{53}Mn and ^{26}Al abundances at that time were ~14×10^{-6} and ~5×10^{-5} respectively.

Nyquist et al. (2001) have studied the Mn-Cr-isotopic system in individual bulk chondrules from the unequilibrated primitive ordinary chondrites Chainpur and Bishunpur. Chondrules are individual submillimeter- to millimeter-sized particles whose mineralogy and internal texture testify to crystallization from a melt. They are an abundant constituent of primitive (undifferentiated) meteorites. The Mn-Cr-isotopic systematics from Chainpur and Bishunpur chondrules suggest a ^{53}Mn/^{55}Mn ratio of ~9.5×10^{-6}. If this value corresponds to the time when these chondrules were formed, this time would be ~11 m.y. prior to the crystallization of LEW 86010, or ~4569 Ma. This value is approximately the same as the time of carbonate formation in Kaidun but ~2 m.y. lower than our preferred estimate for the solar system age of 4571 Ma. Thus, we suggest that the main episode of primary chondrule formation must have occurred within the first ~2 m.y. of solar system history (*Lugmair and Shukolyukov,* 2001).

In several recent studies of ^{26}Mg excesses in Al-rich chondrules (*Russell et al.,* 1996), Mg-rich chondrules (*Kita et al.,* 1998), and ferromagnesian chondrules (*McKeegan et al.,* 2000), it was shown that the inferred ^{26}Al/^{27}Al ratios at the time of their formation (or last isotopic equilibration) were >3–7 × 10^{-6}. The comparison of these values with the "canonical" CAI value of 5 × 10^{-5} indicates that the timespan between CAI formation and formation of these chondrules was not more than ~2 m.y. Thus, both the Mn-Cr and the Al-Mg isotopic systems are consistent in that primary chondrule formation occurred mainly within the first ~2 m.y. of solar system history. This process would have been largely concluded ~4569 Ma. This suggests that most chondrules with inferred ^{26}Al/^{27}Al ratios significantly lower than 3–7 × 10^{-6} and CAIs with ^{26}Al/^{27}Al ratios much lower (by a factor of >~2) than the canonical value of ~5 × 10^{-5} have most likely been metamorphosed or even totally recrystallized (i.e., no clear indication of metamorphism) in the deeper layers of early generations of planetesimals. [*Marhas et al.* (2000), however, prefer a different interpretation. They argue that the absence of a correlation between mineralogical evidence of alteration in carbonaceous chondrite chondrules and their ^{26}Al content suggests either extremely heterogeneous original distribution of ^{26}Al in the solar nebula or an extended timescale of chondrule formation.]

The formation of the first planetesimals may be required to have occurred at the very early stages of solar system evolution. This is because CAIs, which were formed at ~4571 Ma, had to be stored within small planetesimals (several hundred meters to kilometers in size?) in order to prevent their rapid loss into the Sun by gas drag (*Weidenschilling,* 1977). Thus, it appears to be likely that formation of CAIs and small planetesimals took place contemporaneously during several 10^5 yr of CAI formation. The small planetesimals were later disrupted by already larger objects, which caused further mixing of different types of CAIs. At any rate, these small objects were the original carriers of CAIs, which were responsible for later distribution of CAIs among chondrule-bearing planetesimals. Within the following ~2 m.y., large numbers of planetesimals of several tens of kilometers in size had formed. Their interior started to heat up and melt through the decay of ^{26}Al (*Lugmair and Shukolyukov,* 2001; *McSween et al.,* 2002). It is envisioned that chondrule formation may have occurred during this phase by the release of the interior melt as finely dispersed droplets into the surrounding space, caused by collisional disruption of these planetesimals (*Lugmair and Shukolyukov,* 2001). Repeated collisional destruction and reaccretion of these planetesimals was followed by the formation of larger planetary objects several hundred kilometers in size. In many of these larger planetesimals, there was sufficient residual heat and still-extant ^{26}Al for melt to form in their interior. Within ~3 m.y., the molten interior started to chemically differentiate to form a stratified mantle and, most likely, a core. By ~4565 Ma this process came to a conclusion (at least on some asteroids; see below). In the following sections, we will discuss several examples of Mn-Cr dating of differentiation events and other thermal processes occurring within asteroids.

4.2. Asteroid Vesta

An example of a differentiated asteroid is Vesta. A genetic link between the family of HED (howardite-eucrite-diogenite) meteorites and the asteroid Vesta was suggested in the 1970s (*McCord et al.,* 1970). This suggestion was based on the fact that the reflectance spectrum of Vesta matches that of the HED meteorites. However, this idea has long been a subject of debate because of the dynamical difficulties of transporting the HED meteorites to Earth. The finding of more than twenty small asteroids having Vesta-like spectral properties indicates that they are distributed from Vesta to the 3:1 resonance and, thus, demonstrate a dynamically viable route for samples from Vesta to Earth (*Binzel and Xu,* 1993). Most students of Vesta now believe that this asteroid is the parent body (PB) of the HED meteorites [for a review on the history of Vesta, see *Keil et al.* (2002)].

Some of the noncumulate eucrites — abundant constituents among HED meteorites — reveal the former presence of the short-lived radionuclides ^{60}Fe ($T_{1/2}$ = 1.5 m.y.) (*Shukolyukov and Lugmair,* 1993) and ^{26}Al ($T_{1/2}$ = 0.73 m.y.) (*Srinivasan et al.,* 1999). This indicates the antiquity of these meteorites and implies that the differentiation processes within Vesta occurred very early.

Figure 2 illustrates the results of our study of the Mn-Cr-isotopic system in various constituents of the HED PB — noncumulate and cumulate eucrites and diogenites (*Lugmair and Shukolyukov,* 1998). We plotted the measured ^{53}Cr/^{52}Cr ratios for bulk meteorites vs. their respective ^{55}Mn/^{52}Cr ratios. The data points form a well-defined correlation line. Since this line represents a bulk meteorite isochron, no information on the time of crystallization or cooling of individual meteorites can be derived from this diagram. Instead, the slope of the line corresponds to a ^{53}Mn/^{55}Mn ratio of (4.7 ± 0.5) × 10^{-6} at the time of the last Mn/Cr fractionation in the HED mantle. Since any resolvable scatter of the data points from the line does not exist, the source reservoirs of all these meteorites can be assumed to have formed contemporaneously. The Mn-Cr systems of the bulk samples of these meteorites must have remained closed since their formation. From the ^{53}Mn/^{55}Mn ratio for the HED PB of (4.7 ± 0.5) × 10^{-6} and that of LEW 86010 (see above) a relative time for the HED PB mantle fractionation is 7.1 ± 0.8 m.y. prior to angrite crystallization, yielding an absolute time of 4564.8 ± 0.9 Ma. Thus, the time of global mantle fractionation on Vesta postdates the beginning of the solar system by only ~6 m.y. This demonstrates that planetary differentiation processes must have occurred very early in solar system history. The results of thermal modeling of Vesta (*Ghosh and McSween,* 1998) are consistent with this finding.

The ages of individual basaltic achondrites from Vesta (*Lugmair and Shukolyukov,* 1998) suggest that basaltic volcanism occurred within only a few million years of global differentiation. Figure 3 illustrates several examples of internal ^{53}Mn-^{53}Cr isochrons for noncumulate eucrites. The moderately brecciated eucrite Chervony Kut (CK) reveals the highest ^{53}Mn abundance. The slope of the best-fit line yields the ^{53}Mn/^{55}Mn ratio of $(3.7 \pm 0.4) \times 10^{-6}$ at the time of isotopic closure. The difference between this value and that in LEW 86010 corresponds to a time difference of 5.8 ± 0.8 m.y., yielding an absolute age of 4563.6 ± 0.9 Ma. Thus, CK formed almost contemporaneously with the global differentiation of Vesta. The isochron for the eucrite Juvinas (JUV) is shown schematically. Its slope yields the ^{53}Mn/^{55}Mn ratio of $(3.0 \pm 0.5) \times 10^{-6}$. With a Mn-Cr age of 4562.5 ± 1.0 Ma, JUV is slightly younger than CK. In contrast to CK and JUV, the mineral fractions from the eucrite Caldera (CAL) have totally equilibrated ^{53}Cr/^{52}Cr ratios (Fig. 3) (*Wadhwa and Lugmair,* 1996). This indicates that ^{53}Mn had practically fully decayed by the time the ^{53}Mn-^{53}Cr system closed in this meteorite. The upper limit of its ^{53}Mn/^{55}Mn ratio of 1.2×10^{-7} implies that the age of CAL is ≤4545 Ma. Although this young age may correspond to a "cooling age," it is more likely the result of impact melting that reequilibrated the Cr isotopes. Similar examples for reequilibrated Cr isotopes were observed in the mineral fractions of other noncumulate eucrites such as Pomozdino (T ≤ 4554 Ma) and EET 87520 (T ≤ 4549 Ma). The diogenites Shalka and Johnstown and the cumulate eucrite Moore County (not shown here) also show a flat ^{53}Cr/^{52}Cr-isotopic pattern. However, this most likely reflects slow cooling in the deeper zones of the HED PB (*Lugmair and Shukolyukov,* 1998). While the basaltic eucrites are believed to originate from basaltic deposits in the upper layers of the crust, the diogenites and cumulate eucrites are derived from deeper layers.

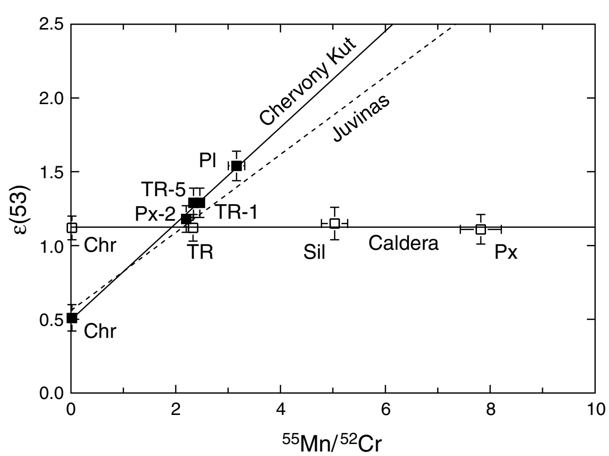

Fig. 3. Manganese-53–chromium-53 systematics for several noncumulate eucrites. Chr = chromite, TR = total rock, Px = pyroxene, Sil = silicates, Pl = plagioclase. The oldest is Chervony Kut (filled squares), clearly showing the presence of live ^{53}Mn at the time of crystallization. The slope of the best-fit line yields the ^{53}Mn/^{55}Mn ratio of $(3.7 \pm 0.4) \times 10^{-6}$ at the time of isotopic closure, corresponding to an absolute age of 4563.6 ± 0.9 Ma. The isochron for the eucrite Juvinas is shown schematically (dashed line). A ^{53}Mn/^{55}Mn ratio of $(3.0 \pm 0.5) \times 10^{-6}$ for Juvinas yields an age of 4562.5 ± 1.0 Ma. In contrast, Caldera (open symbols) had isotopically equilibrated at a time when ^{53}Mn was no longer extant. See text for more details. Data from *Lugmair and Shukolyukov* (1998) and *Wadhwa and Lugmair* (1996).

4.3. Other Differentiated and Undifferentiated Asteroids

Another example for early igneous activity on asteroids is the meteorite Brachina. Brachinites are a unique group of primitive achondrites, which, although near-chondritic in their major-element bulk composition, are distinctly igneous textured with an olivine-rich mineralogy (e.g., *Nehru et al.,* 1983). The study of the Mn-Cr-isotopic system in this unique meteorite has shown that at the time of isotopic closure, the ^{53}Mn/^{55}Mn ratio was $(3.8 \pm 0.4) \times 10^{-6}$ (*Wadhwa et al.,* 1998). This value translates into an absolute age of 4563.7 ± 0.9 Ma and most likely corresponds to the time of extensive thermal metamorphism subsequent to Brachina's formation. Within 2σ errors, this age is similar to that of CK and to the time of global differentiation of the HED PB (4564.8 ± 0.9 Ma). A result of the earliest phases of igneous activity in the asteroid belt, Brachina may be among the earliest generations of achondrites formed in the solar system.

In contrast, the Mn-Cr ages of another type of differentiated meteorites, the pallasites, are much younger. These meteorites consist mainly of metal and olivine and are probably formed at the boundary between the silicate mantle and the metal core of large planetesimals. The Mn-Cr-isotopic system in two pallasites, Omolon (OM) (*Shukolyukov and Lugmair,* 1997) and Eagle Station (ES) (*Shukolyukov and Lugmair,* 2001), is illustrated in Fig. 4. The slope of the best-fit line for ES yields a ^{53}Mn/^{55}Mn ratio of $(1.17 \pm 0.09) \times 10^{-6}$ at the time of isotopic closure. This value corresponds to an absolute age of 4557.5 ± 0.6 Ma. The best-fit line for OM results in a ^{53}Mn/^{55}Mn ratio of $(1.29 \pm 0.19) \times 10^{-6}$, yielding an age of 4558.0 ± 1.0 Ma. This age is indistinguishable from that of ES. The correlation line for ES, although of similar slope to that of OM, passes below the OM best-fit line and the other isochrons for the meteorites with chondritic Mn/Cr ratio (*Shukolyukov and Lugmair,* 2001). This indicates that the ES precursor material had a lower than chondritic Mn/Cr ratio, possibly similar to CV3-type carbonaceous material (*Shukolyukov and Lugmair,* 2000b). This finding, as well as the presence in ES of an anomalous presolar component with an excess of ^{54}Cr, an anomalous O-isotopic composition (*Clayton and Mayeda,* 1996), and the enrichment in refractory siderophile trace elements (*Scott,* 1977), indicates that this pallasite formed within a parent body that is different from that of OM. The younger Mn-Cr ages of the pallasites (~4558 Ma)

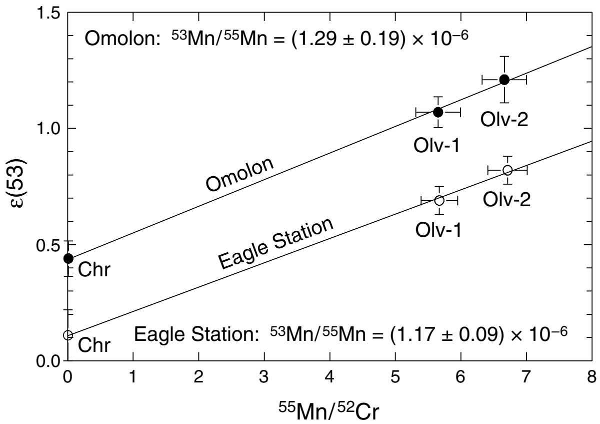

Fig. 4. Manganese-53–chromium-53 systematics in the pallasites Eagle Station and Omolon. Chr = chromite, Ol = olivine. The $^{53}Mn/^{55}Mn$ ratios at the time of isotopic closure are indistinguishable within the uncertainties and yield an age of ~4558 Ma for both meteorites. However, Eagle Station and Omolon originate from different parent bodies (see text). The relatively young Mn-Cr age of the pallasites corresponds to the time when either the interiors of their parent bodies cooled or the parent bodies were disrupted, which allowed rapid cooling of the exposed interior.

reflect the time when either the interiors of large chemically stratified, differentiated planetesimals cooled below the isotopic closure temperature or the planetesimals were disrupted to allow rapid cooling of the exposed interior.

Because of either their small size or relatively late time of formation, some of the planetary objects did not accumulate enough energy (^{26}Al and gravitational energy) for melting but experienced only different degrees of thermal metamorphism. The parent bodies of the sampled chondrites may be some examples of this. The Mn-Cr-isotopic system in the primitive H4 chondrite Ste. Marguerite closed at 4565.0 ± 0.7 Ma (*Polnau and Lugmair,* 2001). The EH4 chondrites Indarch and Abee cooled essentially at the same time (4564–4566 Ma) (*Shukolyukov and Lugmair,* 1999). These results are in good agreement with the recent investigations with the ^{129}I-^{129}Xe chronometer (*Brazzle et al.,* 1999; *Gilmour,* 2000). However, many other chondrites of higher metamorphic grades show metamorphic ages of up to more than 10 m.y. younger. For example, the U-Pb age of the L5–6 chondrite Barwell is ~4538 Ma (*Göpel et al.,* 1994). Most likely this is a result of slow cooling in the deeper zones of the parent asteroid.

5. SUMMARY

We have constructed an absolute timescale for the events in the early solar system based mostly on the data obtained with the Mn-Cr-isotopic chronometer. Some of the results are summarized in Fig. 5. First solids in the early solar system (CAIs) formed ~4571 Ma. Both the Mn-Cr and the Al-Mg timescales are anchored to this time. The formation of small planetesimals (100 m to km in size) occurred almost simultaneously. An early and swift formation of small planetesimals is necessary in order to prevent the rapid loss of CAIs into the Sun. Larger planetesimals (tens of kilometers) accreted during the next few million years. Both the Mn-Cr and the Al-Mg systems are consistent in that primary chondrule formation occurred mostly within the

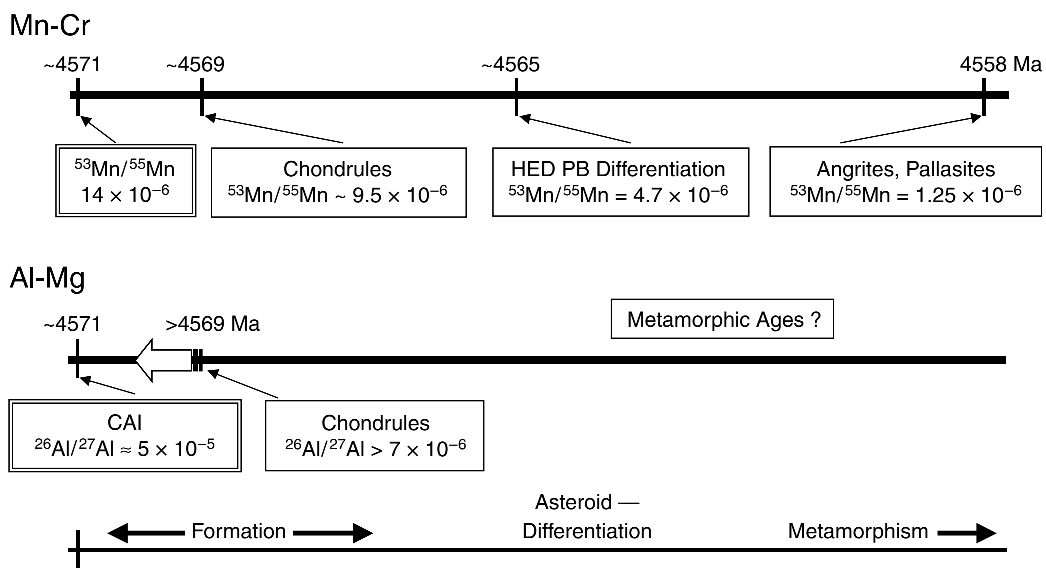

Fig. 5. Manganese-chromium and Al-Mg early solar system timelines. Both the Mn-Cr and Al-Mg system are anchored to the time of 4571 Ma, when most refractory meteorite inclusions (CAI) are believed to have formed. Small planetesimals were formed almost simultaneously to preserve the CAIs. The interiors of many intermediate-sized planetesimals were melted through the decay of ^{26}Al. Within a timespan of about 2 m.y. most primary chondrules appear to have been formed. Larger planetesimals accreted after a few million years. Chemical differentiation, formation of a stratified mantle and a core in these larger bodies came to an end at ~4565 Ma (Vesta). Metamorphic alteration of asteroidal material due to latent heat and collisions persisted for many millions of years. See text for details.

first ~2 m.y. of solar system history and would have been largely concluded ~4569 Ma. It appears that this time was an era of intense thermal processing in inner solar system material due to decay of ^{26}Al. Later collisional disruption of these larger planetesimals distributed chondrules to their ultimate meteorite parent bodies. On yet larger planetesimals (several 100 km) chemical differentiation, formation of a stratified mantle and a core came to a conclusion a few million years later at ~4565 Ma (Vesta). At about the same time (4564–4566 Ma), the outer zones of some chondrite PBs, such as those of the H chondrites and the enstatite chondrites, cooled below temperatures where isotopic closure occurs. The younger ages of pallasites (~4558 Ma) mark the time when either the interiors of their PBs cooled or the PBs were disrupted to allow rapid cooling of the exposed interior. The chondrites of higher metamorphic grade show metamorphic ages up to more than 10 m.y. younger, which is most likely a result of slow cooling due to a deep burial in their PBs. Clearly, accretion, accumulation of heat, and chemical differentiation on larger asteroids occurred on a relatively short timescale, on the order of only ~6 m.y.

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REFERENCES

Birck J.-L. and Allègre C. J. (1985) Evidence for the presence of ^{53}Mn in the early solar system. *Geophys. Res. Lett., 12,* 745–748.

Binzel R. P. and Xu S. (1993) Chips off of asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. *Science, 260,* 186–191.

Boss A. P. and Vanhala H. A. T. (2000) Triggering protostellar collapse, injection, and disk formation. *Space Sci. Rev., 92,* 13–22.

Brazzle R. H., Pravdivtseva O. V., Meshik A. P., and Hohenberg C. M. (1999) Verification and interpretation of the I-Xe chronometer. *Geochim. Cosmochim. Acta, 63,* 739–760.

Cameron A. G. W., Vanhala H., and Hoflich P. (1997) Triggering presolar cloud collapse and injecting material into the presolar nebula. In *Astrophysical Implications of Laboratory Study of Presolar Materials* (T. J. Bernatowicz and E. K. Zinner, eds.), pp. 649–664. American Institute of Physics, New York.

Carlson R. W. and Lugmair G. W. (2000) Timescales of planetesimal formation and differentiation based on extinct radioisotopes. In *Origin of the Earth and Moon* (R. M. Canup and K. Righter, eds.), pp. 25–44. Univ. of Arizona, Tucson.

Cassen P. and Woolum D. S. (1997) Nebular fractionation and Mn-Cr systematics (abstract). In *Lunar and Planetary Science XXVIII,* pp. 211–212. Lunar and Planetary Institute, Houston.

Chen J. H. and Tilton G. R. (1976) Isotopic lead investigations on the Allende carbonaceous chondrite. *Geochim. Cosmochim. Acta, 40,* 635–643.

Clayton D. D. and Jin L. (1995) A new interpretation of ^{26}Al in meteoritic inclusions. *Astrophys. J. Lett., 451,* L87–L91.

Clayton R. N. and Mayeda T. K. (1996) Oxygen isotope studies of achondrites. *Geochim. Cosmochim. Acta, 60,* 1999–2017.

Dickin A. P. (1995) *Radiogenic Isotope Geology.* Cambridge Univ., Cambridge. 452 pp.

Ghosh A. and McSween H. Y. Jr. (1998) A thermal model for the differentiation of asteroid 4 Vesta, based on radiogenic heating. *Icarus, 134,* 187–206.

Gilmour D. J. (2000) The extinct radionuclide timescale of the early solar system. *Space Sci. Rev., 92,* 123–132.

Göpel C., Manhés G., and Allègre C. J. (1991) Constraints on the time of accretion and thermal evolution of chondrite parent bodies by precise U-Pb dating of phosphates (abstract). *Meteoritics, 26,* 338.

Göpel C., Manhés G., and Allègre C. J. (1994) U-Pb systematics of phosphates from equilibrated ordinary chondrites. *Earth Planet. Sci. Lett., 121*, 153–171.

Hsu W., Huss G. R., and Wasserburg G. J. (2000) Compound CAI and multi-stage formation: Evidence of ^{26}Al abundances from the Allende 5241 CAI (abstract). In *Lunar and Planetary Science XXXI,* Abstract #1734. Lunar and Planetary Institute, Houston (CD-ROM).

Hutcheon I. D., Weisberg M. K., Phinney D. L., Zolensky M. E., Prinz M., and Ivanov A. V. (1999) Radiogenic ^{53}Cr in Kaidun carbonates: Evidence for very early aqueous activity (abstract). In *Lunar and Planetary Science XXX,* Abstract #1722. Lunar and Planetary Institute, Houston (CD-ROM).

Keil K. (2002) Geological history of asteroid 4 Vesta: The "smallest terrestrial planet." In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Kita N. T., Nagahara H., Togashi S., and Morishita Y. (1998) New evidence of aluminum-26 from ferrous-oxide-rich chondrule in Semarkona (LL3.0) (abstract). *Meteoritics & Planet. Sci., 33,* A83–A84.

Lugmair G. W and Galer 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}Cr systematics. *Geochim. Cosmochim Acta, 62,* 2863–2886.

Lugmair G. W. and Shukolyukov A. (2001) Early solar system events and timescales. *Meteoritics & Planet. Sci., 36,* 1017–1026.

MacPherson G. J., Wark D. A., and Armstrong J. T. (1988) Primitive material surviving in chondrites: Refractory inclusions. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 436–461. Univ. of Arizona, Tucson.

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.

Marhas K. K., Hutcheon I. D., Krot A. N., Goswami J. N., and Komatsu M. (2000) Aluminum-26 in carbonaceous chondrite chondrules (abstract). *Meteoritics & Planet. Sci., 35,* A102.

McCord T. B., Adams J. B., and Johnson T. V. (1970) Asteroid Vesta: Spectral reflectivity and compositional implications. *Science, 168,* 1445–1447.

McKeegan K. D., Greenwood J. P., Leshin L. A., and Cosarinsky M. (2000) Abundance of ^{26}Al in ferromagnesian chondrules of unequilibrated ordinary chondrites (abstract). In *Lunar and Planetary Science XXXI,* Abstract #2009. Lunar and Planetary Institute, Houston (CD-ROM).

McSween H. Y. Jr., Ghosh A., Grimm R. E., Wilson L., and Young E. D. (2002) Thermal evolution models of asteroids. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Meibom A. and Clark B. E. (1999) Evidence for the insignificance of ordinary chondritic material in the asteroid belt. *Meteoritics & Planet. Sci., 34,* 7–24.

Nehru C. E., Prinz M., Delaney J. S., Dreibus G., Palme H., Spettel B., and Wänke H. (1983) Brachina: A new type of meteorite, not a chassignite. *Proc. Lunar Planet. Sci. Conf. 14th*, in *J. Geophys. Res., 88,* B237–B244.

Nyquist L. E., 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.

Papanastassiou D. A. (1986) Cr isotopic anomalies in the Allende meteorite. *Astrophys J. Lett., 308,* L27–L30.

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

Podosek F. A. and Nichols R. H. Jr. (1997) Short-lived radionuclides in the solar nebula. In *Astrophysical Implications of the Laboratory Study of Presolar Materials* (T. J. Bernatowicz and E. K. Zinner, eds.), pp. 617–647. American Institute of Physics, New York.

Podosek F. A., Ott U., Brannon J. C., Neal C. R., Bernatowicz T. J., Swan P., and Mahan S. E. (1997) Thoroughly anomalous chromium in Orgueil. *Meteoritics & Planet. Sci., 32,* 617–627.

Polnau E. and Lugmair G. W. (2001) Mn-Cr isotope systematics in the two ordinary chondrites Richardton (H5) and Ste. Marguerite (H4) (abstract). In *Lunar and Planetary Science XXXII,* Abstract #1527. Lunar and Planetary Institute, Houston (CD-ROM).

Rotaru M., Birck J.-L., and Allègre C. J. (1992) Clues to early solar system history from chromium isotopes in carbonaceous chondrites. *Nature, 358,* 465–470.

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.

Scott E. R. D. (1977) Geochemical relationships between some pallasites and iron meteorites. *Mineral. Mag., 41,* 265–272.

Shu F. H., Shang H., Glassgold E., and Lee T. (1997) X-rays and fluctuating X-wind from protostars. *Science, 277,* 1475–1479.

Shukolyukov A. and Lugmair G. W. (1993) ^{60}Fe in eucrites. *Earth Planet. Sci. Lett., 119,* 159–166.

Shukolyukov A. and Lugmair G. W. (1997) The ^{53}Mn-^{53}Cr isotope system in the Omolon pallasite and the half-life of ^{187}Re (abstract). In *Lunar and Planetary Science XXVIII,* pp. 1315–1316. Lunar and Planetary Institute, Houston.

Shukolyukov A. and Lugmair G. W. (1999) The ^{53}Mn-^{53}Cr isotope systematics of the enstatite chondrites (abstract). In *Lunar and Planetary Science XXX,* Abstract #1093. Lunar and Planetary Institute, Houston (CD-ROM).

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

Shukolyukov and Lugmair G. W. (2000b) Cr isotope anomalies in the carbonaceous chondrites Allende and Orgueil and a potential connection between 54-Cr and oxygen isotopes (abstract). *Meteoritics & Planet. Sci., 35,* A146.

Shukolyukov A. and Lugmair G. W. (2001) Cr isotope systematics in the pallasite Eagle Station: Chronology and evidence for a genetic link to carbonaceous chondrites (abstract). In *Lunar and Planetary Science XXXII,* Abstract #1365. Lunar and Planetary Institute, Houston (CD-ROM).

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.

Störzer D. and Pellas P. (1977) Angra dos Reis: Plutonium distri bution and cooling history. *Earth Planet. Sci. Lett*., *35,* 285–293.

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.

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., Shukolyukov A., and Lugmair G. W. (1998) ^{53}Mn-^{53}Cr systematics in Brachina: A record of one of the earliest phases of igneous activity on an asteroid (abstract). In *Lunar and Planetary Science XXIX,* Abstract #1480. Lunar and Planetary Institute, Houston (CD-ROM).

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

Weidenschilling S. J. (2000) Formation of planetesimals and accretion of the terrestrial planets. *Space Sci. Rev., 92,* 295–310.

Zinner E. and Göpel C. (1992) Evidence for ^{26}Al in feldspars from the H4 chondrite Ste. Marguerite (abstract). *Meteoritics, 27,* A311–A312.