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On early Solar System chronology: Implications of an heterogeneous spatial distribution of ^{26}Al and ^{53}Mn

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Abstract—Early Solar System chronology is usually built with the assumption that the distribution of short-lived radionuclides was homogeneous through the solar accretion disk. At present, there is no unambiguous evidence for a homogeneous distribution of short-lived radionuclides in the solar accretion disk, while some data point to a heterogeneous distribution of short-lived radionuclides. In this paper, we explore a possible chronology based on a heterogeneous distribution of ^{26}Al and ^{53}Mn in the accretion disk. Our basic assumption is that the different abundances of extinct short-lived radionuclides in calcium-aluminium-rich inclusions (CAIs) and chondrules are due to spatial rather than temporal differences. We develop a simple model where CAIs and chondrules form contemporaneously, in different spatial locations, and are characterised by distinct initial ^{26}Al and ^{53}Mn abundances. In this model, all evolved bodies are supposed to be originally chondritic, i.e., to be made of a mixture of CAIs, chondrules, and matrix. This mixture determines the initial content in ^{26}Al and ^{53}Mn of a chondritic parent-body as a function of its CAI and chondrule abundance fraction. This approach enables us to calculate coherent ^{26}Al and ^{53}Mn ages from the agglomeration of the parent-body precursors (CAIs and chondrules) until the isotopic closure of ^{26}Al and ^{53}Mn, thereafter called ^{26}Al-^{53}Mn age. We calculate such ^{26}Al-^{53}Mn ages for a diversity of evolved objects, with the constraint that they should be found for realistic chondritic parent-body precursors, i.e., objects having similar or identical petrograpy to the existing chondrite groups. The so defined age of the d'Orbigny angrite is 4.3 ± 1.1 Myr, for the Asuka-881394 eucrite 2.8 ± 1.0 Myr, for the H4 chondrite Sainte Marguerite ~3 Myr, and for H4 Forest Vale ~5 Myr. The calculated ^{26}Al-^{53}Mn ages give timescales for the evolution of the respective parent-bodies/meteorites that can be investigated in the light of further petrographic studies. We anchor the calculated relative chronology to an absolute chronology using absolute Pb-Pb ages and relative Hf-W ages of the objects under scrutiny. The precursors of Sainte Marguerite and Forest Vale agglomerated at the same time (~4565.8 ± 1.2 Ma ago). The precursors of eucrites (Asuka-881394) agglomerated 4564.8 ± 1.2 Ma ago. The precursors of angrites agglomerated late (4561.5 ± 1.8 Ma ago). Our model provides a fully compatible Al-Mg/Mn-Cr/Pb-Pb chronology, and is shown to be robust to reasonable changes in the input parameters. The calculated initial ^{26}Al/^{27}Al ratios are high enough to have ^{26}Al as a possible heat source for differentiation. *Copyright © 2005 Elsevier Ltd*

1. INTRODUCTION

Elucidating the chronology of early processes in the Solar System is one of the major goals of planetary sciences. Determining timescales for the formation of the earliest solids (such as chondrules and calcium-aluminium-rich inclusions [CAIs]), as well as asteroidal metamorphism and differentiation (Wadhwa and Russell, 2000) is especially important, because it provides a powerful way of linking meteorite laboratory data with astronomical observations. One of the most potentially useful tools in establishing a fine-scale early Solar System chronology has been short-lived radionuclides. These radioactive isotopes, known to have been alive in the early Solar System, are now extinct, but have left their mark in meteorites in the form of excesses of their daughter decay products (Russell et al., 2001). Although the half-lives of short-lived radionuclides that have been considered to date by the cosmochemical community range from 53 days for ^{7}Be to 103 Ma for ^{146}Nd (Birck, 2004; Chaussidon et al., 2004; Russell et al., 2001), only short-lived radionuclides with half-life of ~ Ma can be used to date early Solar System events that took place on Ma timescales such as CAI and chondrule formation, or asteroid differentiation. Among short-lived radionuclides with half-lives ~ Ma, only ^{26}Al ($T_{1/2}$ = 0.74 Ma) or ^{53}Mn ($T_{1/2}$ = 3.7 Ma) have been measured both in primitive chondrite components (CAIs and chondrules) and in evolved (melted or equilibrated) objects. Recently, ^{60}Fe has been measured in ordinary chondrite chondrules (Mostefaoui et al., 2004; Tachibana and Huss, 2003). However, there is only an upper limit for the initial ^{60}Fe/^{56}Fe ratio of CAIs (Birck and Lugmair, 1988), while the initial ^{60}Fe/^{56}Fe ratio of eucrites is highly variable (Quitté and Halliday, 2004; Shukolyukov and Lugmair, 1993). In this paper, we will try to build a coherent chronology based on ^{26}Al and ^{53}Mn following early work by a diversity of authors (Gilmour and Saxton, 2001; McKeegan and Davis, 2004; Swindle et al., 1996; Zinner and Göpel, 2002).

Chronological models usually rely on the assumption that short-lived radionuclides are spatially homogeneously distributed in the solar accretion disk. Applied to ^{26}Al, this assumption leads to a time difference of ~2 Ma between CAI formation and the formation of the first chondrules (Huss et al., 2001;

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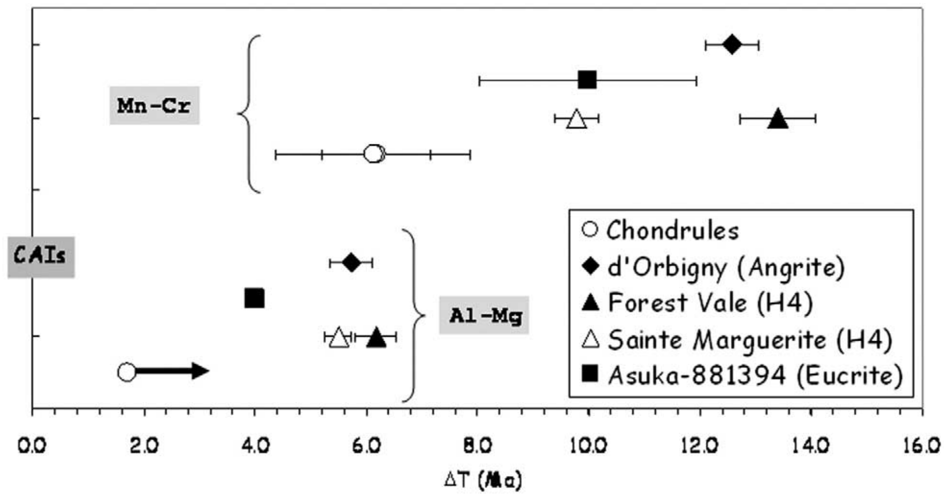

Fig. 1. Relative ^{26}Al and ^{53}Mn chronology based on the assumption of an homogeneous distribution of ^{26}Al and ^{53}Mn in the solar accretion disk, and calculated using Eqn. 2. Error bars are calculated using the formula $\Delta t = \lambda^{-1}\frac{\Delta\Re}{\Re}$ where λ is the decay constant of ^{26}Al or ^{53}Mn and $\Delta\Re$ the 2σ error on the ^{26}Al or ^{53}Mn initial ratio (the error on the initial ratio $\Re^{SR}_{PB}(0)$ is neglected). In this model, it is implicitly assumed that CAI formation marks the beginning time of the Solar System. With this assumption, there is a ~4 (6) Ma discrepancy between the Al-Mg and Mn-Cr ages for chondrules (eucrites) relative to CAIs. CAIs ^{53}Mn/^{55}Mn and ^{26}Al/^{27}Al initial ratios are 3×10^{-5} (Birck and Allègre, 1985; Nyquist et al., 2001) and 5×10^{-5} (MacPherson et al., 1995) respectively. For chondrules, initial ratios are ^{53}Mn/^{55}Mn = $(0.94 \pm 0.17) \times 10^{-5}$ and $(0.95 \pm 0.31) \times 10^{-5}$ (Nyquist et al., 2001), while the upper limit for ^{26}Al/^{27}Al is 1×10^{-5} (Huss et al., 2001). For Sainte Marguerite, initial ratios are ^{53}Mn/^{55}Mn = $(4.78 \pm 0.36) \times 10^{-6}$ (Polnau and Lugmair, 2001) and ^{26}Al/^{27}Al = $(2.87 \pm 0.64) \times 10^{-7}$ (Zinner and Göpel, 2002). For Forest Vale, initial ratios are ^{53}Mn/^{55}Mn = $(2.42 \pm 0.31) \times 10^{-6}$ (Polnau et al., 2000) and ^{26}Al/^{27}Al = $(1.52 \pm 0.52) \times 10^{-7}$ (Zinner and Göpel, 2002). The Asuka-881394 eucrite has an initial ^{26}Al/^{27}Al of $(1.18 \pm 0.14) \times 10^{-6}$ and an initial ^{53}Mn/^{55}Mn ratio equal to $(4.6 \pm 1.7) \times 10^{-6}$ (Nyquist et al., 2003a). The d'Orbigny angrite has an initial ^{26}Al/^{27}Al of $(2.3 \pm 0.8) \times 10^{-7}$ and an initial ^{53}Mn/^{55}Mn ratio equal to $(2.83 \pm 0.25) \times 10^{-6}$ (Nyquist et al., 2003b).

Russell et al., 1996). Applied to ^{53}Mn, this assumption leads to a time difference of ~ 6–8 Ma between CAIs and chondrule formation using the ^{53}Mn/^{55}Mn ratio proposed for CAI (~ 3–4 $\times 10^{-5}$; Birck and Allègre, 1985; Nyquist et al., 2001). The Al-Mg and Mn-Cr timecales for the CAI-chondrule formation interval (2 vs. 6–8 Ma) are clearly incompatible.

One way to solve the discrepancy between the Al-Mg and the Mn-Cr CAI-chondrule formation interval is to assume that the ^{53}Cr excesses found in CAIs are not only due to the decay of ^{53}Mn, but are obscured by the presence of nucleosynthetic isotopic anomalies (Lugmair and Shukolyukov, 1998; Lugmair and Shukolyukov, 2001). Using precise Pb-Pb absolute ages of CAIs and angrites, as well as the ^{53}Mn/^{55}Mn initial ratio for angrites, Lugmair and Shokolyukov (2001) calculate an initial ratio of ^{53}Mn/^{55}Mn ~ 1.4×10^{-5} for CAIs. This procedure reconciles the Mn-Cr CAI-chondrule timescale with the Al-Mg one. It does not, however, resolve the general discrepancy observed between Al-Mg and Mn-Cr ages for equilibrated chondrites and achondrites as shown in Figure 1. The contradictory age differences between Sainte Marguerite and d'Orbigny (2.8 ± 0.61 Ma for Mn-Cr system vs. 0.2 ± 0.44 for the Al-Mg system) cannot be reconciled assuming that the measured initial ^{53}Mn/^{55}Mn is wrong. Similarly, independently of the initial ^{53}Mn/^{55}Mn chosen as a reference, Asuka-881394 and Sainte Marguerite have about the same Mn-Cr age whereas Asuka-881394 is significantly older than Sainte Marguerite if one considers the Al-Mg age. The contradictory Al-Mg and Mn-Cr chronologies (Fig. 1) suggest that the homogeneity hypothesis which underlies the chronological model shown in Figure 1 may be called into question.

The discrepancy between Al-Mg and Mn-Cr ages could be attributed to a spatial heterogeneity of short-lived radionuclide distribution. Arguments have been put forward both for and against isotopic homogeneity in the early Solar System. It has been argued that the reasonably constant initial ^{26}Al in CAIs implies a widespread and largely homogeneous initial distribution (MacPherson et al., 1995). There are, however, hints in meteoritic data for an heterogeneous distribution of some isotopes in the solar accretion disk. For example, CAIs and chondrules contain different abundances of the stable isotopes of oxygen (Clayton, 1993; McKeegan et al., 1998). It is also well known that CAIs contain widespread isotopic anomalies which are mostly absent in chondrules (Birck, 2004). It is thus not inconceivable that other isotopic systems such as short-lived radionuclides may also show intrinsic differences between these two types of components. Some CAIs, such as hibonite-bearing spherules in CM2 chondrites, have no detectable ^{26}Al (Marhas et al., 2002), clearly different from the most frequent CAI value, ^{26}Al/^{27}Al = 5×10^{-5} (MacPherson et al., 1995). A heterogeneous distribution of ^{53}Mn in the solar accretion disk has been advocated by Lugmair and Shukolyukov (1998) and Shukolyukov and Lugmair (2000) on the basis of the bulk ^{53}Cr/^{52}Cr ratios of the Earth, Mars and the Howardites, Eucrites, Disgenites (HED) achondrites. At present, there is no unambiguous evidence for a homogeneous distribution of short-lived radionuclides in the solar accretion disk, while some

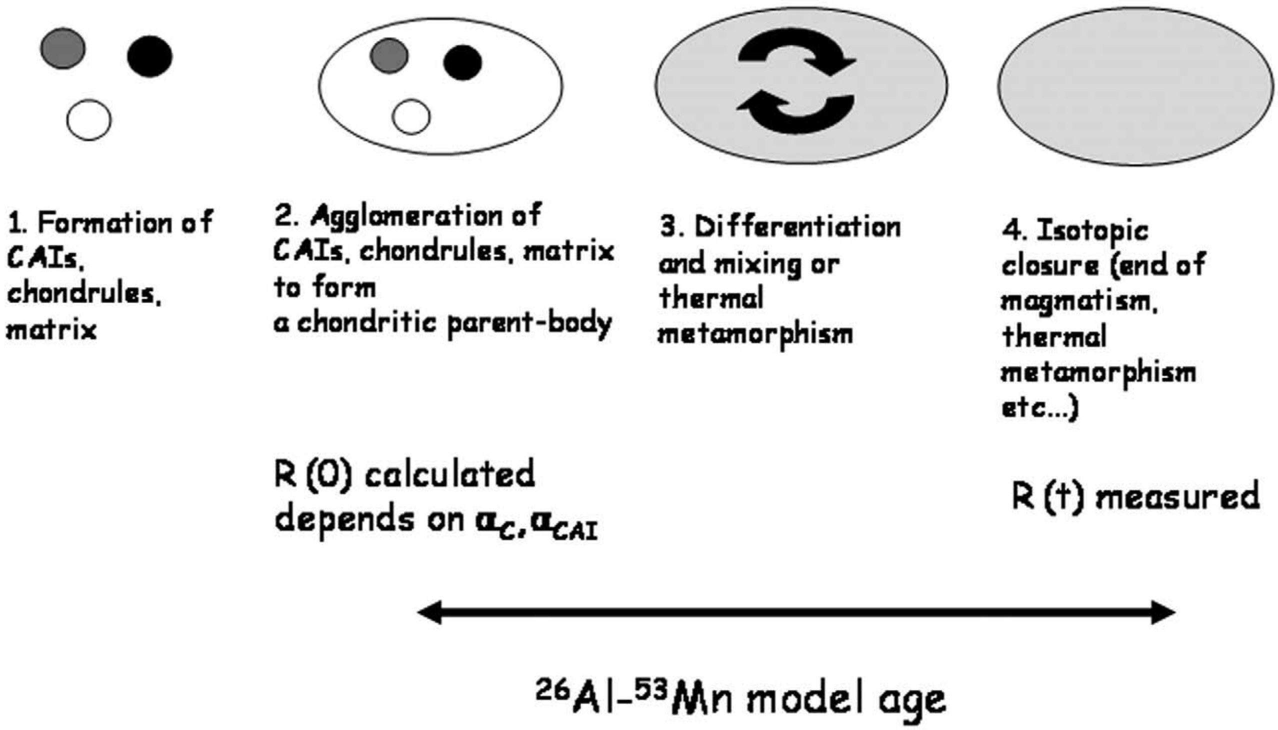

Fig. 2. Diagram depicting the meaning of age in our model. Ages are all understood as ages relative to the agglomeration of precursors until isotopic closure. In our model, data are not referenced to a single beginning event, unlike the model based on an homogeneous assumption of ^{26}Al and ^{53}Mn (see Fig. 1).

data point to a heterogeneous distribution of short-lived radionuclides.

The question of the homogeneity/heterogeneity of short-lived radionuclides is intimately linked to that of their origin. If short-lived radionuclides under consideration are the products of continuous galactic nucleosynthesis (Meyer and Clayton, 2000), they are expected to be homogeneously distributed within the solar accretion disk. Workers promoting an external stellar origin for short-lived radionuclides (e.g., Busso et al., 2003) have defended the idea that short-lived radionuclides were homogeneously distributed within the solar accretion disk, and that a simple chronology can be built (e.g., Zinner, 2003; Zinner and Göpel, 2002). However, the homogeneity of short-lived radionuclides would depend on the injection mechanism of short-lived radionuclides by an Asymptatic Giant Branch (AGB) stellar wind or a supernova shockwave. If short-lived radionuclides have been produced by irradiation (Gounelle et al., 2001; Leya et al., 2003), they are expected to be heterogeneously distributed within the solar accretion disk, since different regions of the disk receive different dosages of accelerated particles (Gounelle et al., 2001).

A key question that underlies any chronology of the early Solar System is the putative minimum 2 Ma time gap between CAIs and chondrules inferred from the Al-Mg chronometer. Although incompatibilities between the timescales inferred from Al-Mg and Mn-Cr systems are not limited to the CAI-chondrule formation timescale (see above), unequivocal demonstration of a formation gap would strongly support the hypothesis of a homogeneous spatial distribution of short-lived radionuclides. This 2 Ma time gap has long been known to be at odds with dynamical studies suggesting that CAIs cannot survive in a quiescent disk for longer than a few 10^5 yr (Weidenschilling, 1977). Storage of CAIs for 2 Ma could have happened within a planetesimal (Hsu et al., 2000), or via turbulence (Cuzzi et al., 2003). As well as preventing CAIs drifting into the Sun, a necessary constraint to any model is that CAIs have largely been kept out of the chondrule-forming region. Fragments of CAIs are extremely rare in chondrules (Bischoff and Keil, 1983; Bischoff and Keil, 1984; Krot et al., in press; Maruyama and Yurimoto, 2003), although titanium isotopic anomalies (Niemeyer, 1988), rare earth patterns (Russell et al., 2002), and ^{16}O-rich isotopic compositions (Jones et al., 2004) in chondrules indicate minor mixing can have taken place between the two reservoirs. Although turbulence can physically prevent CAIs from drifting into the Sun, it does not provide an explanation for the very fine-tuned separation followed by mixing of CAI and chondrule reservoirs. In addition, recent observations of a chondrule-CAI association in a primitive CO3.0 chondrite has led to the suggestion that CAIs and chondrules formed simultaneously (Itoh and Yurimoto, 2003). One of the best ways to assess a possible time difference between CAIs and chondrules is the use of the Pb-Pb chronometer.

Uranium has two long-lived radioisotopes (^{235}U, $T_{1/2}$ = 0.704 Ga and ^{238}U, $T_{1/2}$ = 4.47 Ga) whose inferred abundance within the early Solar System is compatible with expectations from continuous galactic nucleosynthesis (Wasserburg et al., 1996). Uranium isotopes are therefore usually considered to be homogeneously distributed within the Solar System, and precise absolute ages can be calculated using that system. Assuming that the ages provided by these chronometers are crystallisation ages and not metamorphic or secondary ages, the Pb-Pb chronometer can be used to date the time difference between CAIs and chondrules. Early dating of Allende (CV3) CAIs provided an absolute age of 4566 ± 2 Ma (Allègre et al., 1995; Manhès et al., 1988). More precise dating of Efremovka (CV3) CAIs yielded absolute ages of 4567.2 ± 0.7 (CAI E49) and 4567.4 ± 1.1 Ma (CAI E60) (Amelin et al., 2002). Breakthrough measurements of chondrules belonging to the CR2 chondrite Acfer 059 lead to a formation absolute age of 4564.7 ± 0.6 (Amelin et al., 2002). Although it has been argued that dating CAIs and chondrules belonging to a different chondrite group could not be a definitive argument for a 2 Ma time gap (Gounelle and Russell, 2004), this finding has extensively been used to support the 2 Ma timescale between chondrules and CAIs (Amelin et al., 2002; Desch et al., 2004; Wood, 2004; Zinner, 2003). Very recently, Amelin et al. (2004) have measured the Pb-Pb age of chondrules belonging to the Allende (CV3) chondrite and have shown that they have an absolute age of 4566.7 ± 1.0 Ma, indistiguishable (within error bars) from CAIs belonging to the same chondrite group. This finding, although not *stricto sensu* demonstrating our hypothesis, grants it some credit.

The goal of this paper is to determine whether a plausible chronological model can be constructed based on the assumption that ^{26}Al and ^{53}Mn were heterogeneously distributed in the accretion disk. We will, specifically, assume that the abundance of these radionuclides was different in the CAI and chondrule forming regions. This assumption is compatible with an irradiation model for the production of ^{26}Al and ^{53}Mn (Gounelle et al., 2001; Leya et al., 2003), but could also hold true in the case of an heterogeneous distribution of short-lived radionuclides injected by a supernova (Vanhala and Boss, 2002). Our model is an end-member model assuming a simple heterogeneity in the solar accretion disk. As such, it should be viewed as the counterpart of the simple chronological model assuming a homogeneous distribution of ^{26}Al and ^{53}Mn in the disk and depicted in Figure 1.

2. MODEL

2.1. Model Outline

CAIs and chondrules are considered as building blocks of the Solar System. All differentiated bodies are assumed to have chondritic precursors, in the sense that they are initially made of a mixture of CAIs, chondrules, and matrix. The CAIs, chondrules, and matrix that define a given chondritic body are assumed to have formed contemporaneously. The CAI and chondrule forming events can last a few Ma, and components from different chondrite groups might have formed at different times. The different initial abundances of ^{26}Al and ^{53}Mn in CAIs and chondrules are assumed to arise from spatial heterogeneities, possibly due to an irradiation origin of ^{26}Al and ^{53}Mn (Gounelle et al., 2001; Lee et al., 1998; Shu et al., 1997). Matrix is assumed to be a component that contains no or low contents of ^{26}Al or ^{53}Mn. In such a model, the calculated content of a short-lived radionuclide in a given parent-body (PB), $\Re_{PB}^{SR}$, evolves according to the equation:

$$\Re_{PB}^{SR}(t) = \frac{\sum_{i=1}^{i=3} \alpha_i x_i C_i}{\sum_{i=1}^{i=3} \alpha_i C_i} e^{-\lambda t} = \Re_{PB}^{SR}(0) e^{-\lambda t} \tag{1}$$

where the index i can take three values: C for chondrules, CAI for CAI, and M for matrix. λ is the decay constant of the short-lived radionuclide. α_C, α_{CAI}, and α_M are the chondrule, CAI, and matrix abundances of the chondritic precursor of the parent-body under scrutiny. C_C, C_{CAI}, and C_M are the abundance of the stable isotope S in the chondrules, CAIs, and matrix, respectively. x_C, x_{CAI}, and x_M are respectively the ratios R/S in chondrules, CAIs, and matrix at time $t = 0$, defined as the time when CAIs, chondrules, and matrix agglomerate to make a parent-body. The short-lived radionuclide model age of a metamorphosed or differentiated parent-body PB, t_{PB}^{SR}, can be calculated from Eqn. 1:

$$t_{PB}^{SR} = -\lambda^{-1} \ln \frac{\Re_{PB}^{SR}}{\Re_{PB}^{SR}(0)} \tag{2}$$

where $\Re_{PB}^{SR}$ is the *measured* ratio R/S in the considered parent-body, and $\Re_{PB}^{SR}(0)$ is the *calculated* initial value given by Eqn. 1.

Because of the constraint $\alpha_M = 1 - \alpha_C - \alpha_{CAI}$, t_{PB}^{SR} depends only on α_C and α_{CAI} for a given chemical model, i.e., a given set of C_i. For given abundances of CAIs (α_{CAI}) and chondrules (α_C), it is possible to determine *one* ^{26}Al-^{53}Mn age satisfying the equation:

$$t_{PB}^{26\mathrm{Al}}(\alpha_{CAI}, \alpha_C) = t_{PB}^{53\mathrm{Mn}}(\alpha_{CAI}, \alpha_C) \tag{3}$$

The model output is a set of ^{26}Al -^{53}Mn ages, which is a function of the CAIs and chondrule abundances. Because the CAI and chondrule abundances of a chondritic parent-body vary within a limited range (Scott et al., 1996), we hope to identify a class of ^{26}Al-^{53}Mn ages that are coherent with known chondritic objects. Our model age encompasses both ^{26}Al and ^{53}Mn ages, and counts the time since the agglomeration of chondrules and CAIs to form a parent-body until Al-Mg and Mn-Cr isotopic closure in the same parent-body. We will therefore call it a ^{26}Al-^{53}Mn age. The basic assumptions and signification of our model are illustrated in Figure 2.

2.2. Model Assumptions, Input Data, and Free Parameters

For the purpose of this model, we assume that the closure temperature for Mn-Cr and Al-Mg systems is the same. Measurements of diffusion in feldspar have been reported by LaTourette and Wasserburg (1998). These authors showed that a temperature of ~450°C can be considered as a closure temperature for Mg. For the Mn-Cr system there have been no similar studies. We note that all chronological models based on short-lived radionuclides (e.g., Zinner and Göpel, 2002) need to make the same assumption of an identical closure time for the isotopic systems of interest.

We also assume that we have access to both the chemical composition and the original content of short-lived radionuclides of the three components, CAIs, chondrules, and matrix. A diversity of processes can have obscured these records, such

Table 1. Input data for the model.

	CM model			CV model			OC model		
	Chondrules	CAIs[a]	Matrix	Chondrules	CAIs[a]	Matrix	Chondrules	CAIs[a]	Matrix
Al	5600[b]	18%	6500[c]	18600[d]	18%	13000[d]	12000[e]	18%	11100[e]
Mn	1500[b]	20	1700[c]	1500[d]	20	1600[d]	4000[e]	20	2500[e]
$^{26}Al/^{27}Al$	1×10^{-5}	5×10^{-5}	0	1×10^{-5}	5×10^{-5}	0	1×10^{-5}	5×10^{-5}	0
$^{53}Mn/^{55}Mn$	0.96×10^{-5}	3×10^{-5}	0	0.96×10^{-5}	3×10^{-5}	0	0.96×10^{-5}	3×10^{-5}	0

Data are in ppm unless otherwise stated.
[a] Data from Sylvester et al. (1993).
[b] Data from Rubin and Wasson (1986).
[c] Data from Zolensky et al. (1993).
[d] Data from Rubin and Wasson (1987).
[e] Data from Rubin and Pernicka (1989).

as protracted residence in the accretion disk, hydrothermal alteration, or thermal metamorphism. Because of its fine-grained nature, matrix is especially sensitive to secondary processes. The input data presented below are our best present knowledge of the sometimes obscured record of chondritic components.

A last important assumption is that the initial ^{26}Al and ^{53}Mn initial contents measured now in CAIs and chondrules are the abundances at the time of accretion, rather than at the time of formation of these primitive components. Because dynamic timescales in the accretion disk are likely to be short compared to the half-lives of ^{26}Al and ^{53}Mn (Weidenschilling, 1977), it seems justified to adopt as initial $^{26}Al/^{27}Al$ and $^{53}Mn/^{55}Mn$ ratios, the values at crystallisation.

The model inputs are the chemical composition of the precursor (C_i, Table 1), the abundance of ^{26}Al and ^{53}Mn in CAIs and chondrules (x_i, Table 1), and the abundance of ^{26}Al and ^{53}Mn in the objects of which we calculate the age. All these parameters are adopted according to experimental measurements. The uncertainties of the model due to these parameters will be discussed below in section 4.5.

For the chemical compositions of the chondritic precursor, we will explore three possible compositions: CM, CV, and OC (see Table 1). For CAIs, we assume the same average composition for the three models. This is because CAIs are so rare in ordinary chondrites (Russell et al., 1996) that a bulk average chemistry is difficult to define. However, CAIs from ordinary chondrites are similar in mineralogy and mineral chemistry to common types from carbonaceous chondrites (Russell et al., 1996). Likewise, CAIs have been extensively altered in CM2s, so their initial chemistry is obscured (Lee and Greenwood, 1994). Thus a simple CV CAI chemistry was adopted in all three models (Sylvester et al., 1993). Abundance data for CM chondrite chondrules and matrix are from Rubin and Wasson (1986) and Zolensky et al. (1993) respectively. Abundance data for CV chondrite chondrules and matrix are from Rubin and Wasson (1987). Abundance data for OC chondrules and matrix are from Rubin and Pernicka (1989).

Decades of measurements with the ion probe have shown that most CAIs are characterized by an $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$ at their final heating event (MacPherson et al., 1995). Recently it has been reported that whole rock CAIs could have had an initial $^{26}Al/^{27}Al$ ratio of $6–7 \times 10^{-5}$ (Galy et al., 2004). However, intramineral measurements of anorthite consistently yield a lower initial $^{26}Al/^{27}Al$ of $4–5 \times 10^{-5}$ (Young et al., 2005), suggesting that the aluminium isotopes had this composition during the last CAI processing event. Therefore we assume this is the most valid value to assume at time of accretion. Similarly, we will ignore the rare CAIs that have low abundance of ^{26}Al, such as FUN and some hibonite-rich inclusions (MacPherson et al., 1995). We will discuss in section 4.5 the dependence of our model on this input parameter.

The initial $^{26}Al/^{27}Al$ ratio of chondrules has proved to be more difficult to measure than that of CAIs because of the lack of Al-rich phases in these objects. A large number of chondrules have no detectable ^{26}Al (Mostefaoui et al., 2002; Russell et al., 1996; Srinivasan et al., 2000b). In ordinary chondrites, chondrules' $^{26}Al/^{27}Al$ initial ratios vary between $(0.45 \pm 0.21) \times 10^{-5}$ and $(2.28 \pm 0.73) \times 10^{-5}$ (Huss et al., 2001; Kita et al., 2000; McKeegan et al., 2000; Mostefaoui et al., 2002; Russell et al., 1996). In carbonaceous chondrites, a similar range $[(0.24 \pm 0.17) \times 10^{-5}$ to $(2.5 \pm 0.8) \times 10^{-5}]$ is observed (Kunihiro et al., 2004; Marhas et al., 2000; Srinivasan et al., 2000a; Srinivasan et al., 2000b). No difference has been observed so far between Al-rich chondrules and "normal" ferromagnesian chondrules. Calculating an average initial ^{26}Al content for chondrules is difficult, and may be meaningless because most of the data bear on isotopic anomalies detected in plagioclase, and plagioclase is now known to easily reequilibrate its Mg isotopic composition (LaTourette and Wasserburg, 1998; McKeegan et al., 2004). Also, measurements are biased towards chondrules that contain phases with high Al/Mg, introducing a possible bias to the data. A median $^{26}Al/^{27}Al$ value of 1×10^{-5} has been adopted for both ordinary and carbonaceous chondrite chondrules, because it is the median value for less equilibrated chondrites (Huss et al., 2001). As we will discuss later on (section 4.5), our model depends very little on that value.

In pioneering papers, Birck and Allègre (1985, 1988) reported Mn-Cr measurements of two Allende CAIs. They proposed that CAIs had formed with an average initial $^{53}Mn/^{55}Mn$ abundance ratio of $(4.37 \pm 1.07) \times 10^{-5}$ (Birck and Allègre, 1985; Birck and Allègre, 1988). More recent measurements have confirmed this value (Nyquist et al., 2001; Papanastassiou et al., 2002). Nyquist et al. (2001) propose an initial value of $^{53}Mn/^{55}Mn$ of $(2.81 \pm 0.31) \times 10^{-5}$, and Papanastassiou et al. (2002) report a spread in initial values ranging from 1.01×10^{-5} to 12.5×10^{-5}. The span in the initial $^{53}Mn/^{55}Mn$ ratio in CAIs has been interpreted as resulting from alteration (Papanastassiou et al., 2002). In this paper, we will adopt an initial ^{53}Mn/^{55}Mn ratio of 3×10^{-5} compatible with most measurements. It will be shown later on (section 4.5) that our model does not depend critically on this value.

Nyquist et al. (2001) reported Mn-Cr data on unequilibrated ordinary chondrite chondrules. They found that Chainpur and Bishunpur chondrules formed with an initial ^{53}Mn/^{55}Mn ratio equal to $(0.94 \pm 0.17) \times 10^{-5}$ and $(0.95 \pm 0.31) \times 10^{-5}$ respectively. No data are available so far for the initial ^{53}Mn/^{55}Mn ratio in chondrules from carbonaceous chondrites. Lacking such information, we will adopt the same initial ratio as for ordinary chondrite chondrules.

The short-lived radionuclides content of matrix is not well characterised. No isochrons have so far been reported for unambiguous matrix minerals. Feldspars in Sainte Marguerite and Forest Vale have been interpreted as recrystallised matrix minerals (Zinner and Göpel, 2002), therefore their ^{26}Al content records the parent-body metamorphism, rather than the initial content of matrix. The ^{53}Cr excesses recorded in the CI1 chondrites, almost exclusively composed of fine-grained matrix, correlate with the Mn/Cr ratio, indicating the past presence of ^{53}Mn (Birck et al., 1999; Rotaru et al., 1992). Because the matrix of CI1 chondrites has been severely processed and might have included high-temperature components such as CAIs and chondrules, the initial ^{53}Mn/^{55}Mn of CI1 chondrites cannot be taken as the initial ^{53}Mn/^{55}Mn ratio of matrix. We assume here that the matrix component of chondrites does not contain short-lived radionuclides.

Equilibrated or melted objects for which both ^{26}Al and ^{53}Mn precise data are available are rare. The Asuka-881394 eucrite has an initial ^{26}Al/^{27}Al of $(1.18 \pm 0.14) \times 10^{-6}$ and an initial ^{53}Mn/^{55}Mn ratio equal to $(4.6 \pm 1.7) \times 10^{-6}$ (Nyquist et al., 2003b). Recently, Wadhwa et al. (2004) have found for Asuka-881394 an initial ratio ^{26}Al/^{27}Al of $(1.39 \pm 0.07) \times 10^{-6}$ compatible with that found by Nyquist et al. (2003b). The d'Orbigny angrite has an initial ^{26}Al/^{27}Al of $(2.3 \pm 0.8) \times 10^{-7}$ and an initial ^{53}Mn/^{55}Mn ratio equal to $(2.83 \pm 0.25) \times 10^{-6}$ (Nyquist et al., 2003a). Zinner and Göpel (2002) have measured the Mg isotopic composition of feldspars in H4 ordinary chondrites, and found initial ratios ^{26}Al/^{27}Al of $(2.87 \pm 0.64) \times 10^{-7}$ and $(1.52 \pm 0.52) \times 10^{-7}$ for Sainte Marguerite and Forest Vale, respectively. Polnau and collaborators have reported initial ^{53}Mn/^{55}Mn ratios of $(4.78 \pm 0.36) \times 10^{-6}$ and $(2.42 \pm 0.31) \times 10^{-6}$ for Sainte Marguerite and Forest Vale, respectively (Polnau and Lugmair, 2001; Polnau et al., 2000).

Looking at Eqns. 1, 2, and 3, one can see that all the constrained input data of the models can be obtained from the literature. The free parameters are the chondrule fraction (α_C) and the CAI fraction (α_{CAI}).

3. RESULTS

3.1. The ^{26}Al- ^{53}Mn Ages of the Asuka-881394 Eucrite and the d'Orbigny Angrite

In Figures 3 and 4, for a series of CAI abundances, we plot the Asuka-881394 (d'Orbigny) calculated ^{26}Al-^{53}Mn ages vs. the chondrule fraction. In other words, we present the solutions of Eqn. 3. For example, for a CV precursor having 0% CAI for the d'Orbigny parent-body, a ^{26}Al-^{53}Mn age of 3.4 Ma is found if the chondrule fraction is ~60%. Because we do not know precisely the chondritic precursors of the angrite and the eucrite parent-body, we will accept as reasonable solutions, all that have a CAI abundance between 0 and 10% corresponding to the variation range of CAIs within chondrite groups (Scott et al., 1996). Even with this broad range of possible initial compositions, ^{26}Al-^{53}Mn ages are quite well constrained, and remain within a 2 Ma variation range (see Figs. 3, 4, and Table 2).

The ^{26}Al-^{53}Mn ages of the Asuka-881394 eucrite and of the d'Orbigny angrite are shown in Table 2 (see also Figs. 3 and 4). For the OC model the eucrite ^{26}Al-^{53}Mn age varies between 1.7 and 3.6 Ma (for a CAI abundance of 0 and 10% respectively). For the CM model the eucrite age varies between 1.9 and 3.8 Ma (for a CAI abundance of 0 and 10% respectivey). For the CV model the eucrite ^{26}Al-^{53}Mn age varies between 2.0 and 3.5 Ma (for a CAI abundance of 0 and 10% respectively). For the OC model the angrite ^{26}Al-^{53}Mn age varies between 3.2 and 5.3 Ma (for a CAI abundance of 0 and 10% respectively). For the CM model the angrite ^{26}Al-^{53}Mn age varies between 3.4 and 5.5 Ma (for a CAI abundance of 0 and 10% respectively). For the CV model the angrite ^{26}Al-^{53}Mn age varies between 3.6 and 5.2 Ma (for a CAI abundance of 0 and 10% respectively). Overall, the ^{26}Al-^{53}Mn ages of the Asuka-881394 eucrite and the d'Orbigny angrite vary between 1.7 and 3.8 Ma and between 3.2 and 5.5 Ma respectively. We therefore ascribe ages of 2.8 ± 1 Ma and 4.3 ± 1.1 Ma after the agglomeration of the precursors to the cooling of the Asuka-881394 eucrite and the d'Orbigny angrite respectively.

3.2. The ^{26}Al-^{53}Mn Ages of the H4 Chondrites Sainte Marguerite and Forest Vale

The H4 meteorites Sainte Marguerite and Forest Vale represent a special case, in that they are not differentiated meteorites, but metamorphosed chondrites. For these meteorites, constraints are tighter because we know a priori their chondrule (60–80%) (Jones et al., 2000; Scott et al., 1996) and CAI (~0.1%) abundance. In Figures 5 and 6 the evolution of *both* the ^{26}Al and ^{53}Mn ages are shown as a function of the chondrule abundance for Forest Vale and Sainte Marguerite respectively (with a 0.1% abundance of CAIs). Note that this representation is different from the one adopted in Figures 3 and 4, since we have fixed the abundance of CAIs to be 0.1%, therefore the ^{26}Al and ^{53}Mn ages depend on one parameter only, the chondrule abundance, α_C. In this case, the ^{26}Al-^{53}Mn age can be directly read on the graph as the intersection—within error bars—between the curves.

If a median chondrule abundance of 80% is chosen for H4 chondrites, a ~3 Ma ^{26}Al-^{53}Mn age is found for Sainte Marguerite. For Forest Vale, the two curves do not intersect within error bars. This is mainly due to the fact that the ^{26}Al age is too high, i.e., that the ^{26}Al content of Forest Vale is too low. Indeed, the Forest Vale isochron shown by Zinner and Göpel (2002) is quite perturbed, and error bars on the initial ^{26}Al content might be higher than the ones used in our calculation. We therefore ascribe a ~5 Ma ^{26}Al-^{53}Mn age to Forest Vale

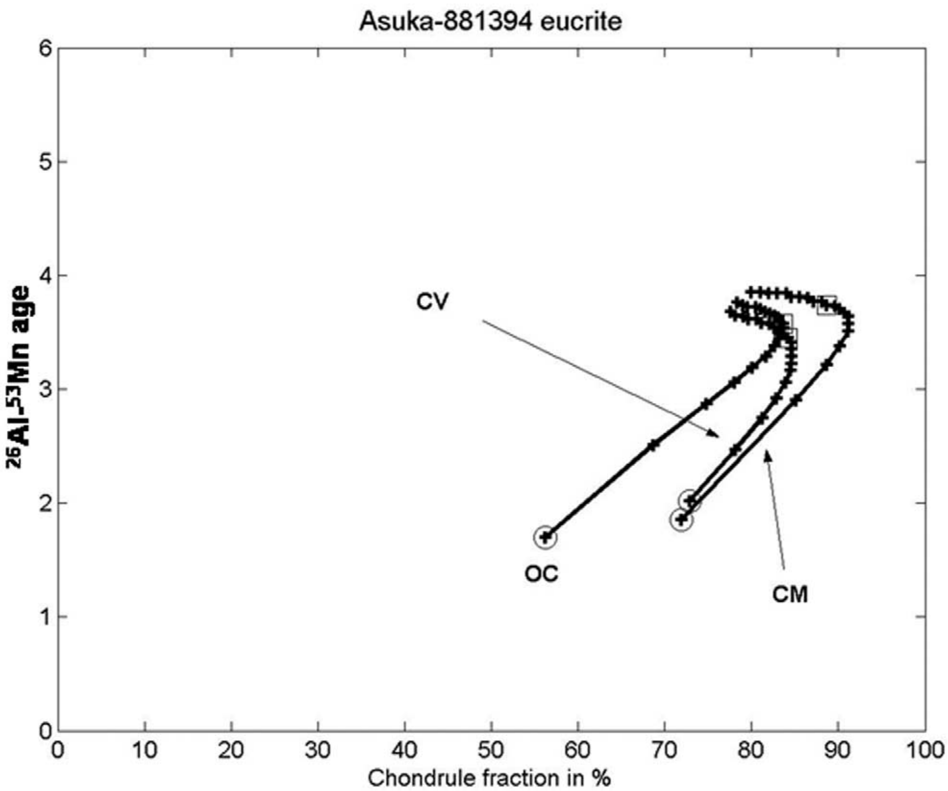

Fig. 3. ^{26}Al-^{53}Mn ages plotted vs. the chondrule abundance for the Asuka-881394 parent-body for a variety of chemical models (OC, CM, and CV chondrites). This graph is the locus of the solutions of the equation t_{PB}^{26Al} (α_{CAI},α_{C}) = t_{PB}^{53Mn}(α_{CAI},α_{C}) for Asuka-881394. Crosses mark the varying abundance of CAIs. They start at 0% (circles), and are plotted every one 1% until 20%. The squares mark the run with 10% CAIs.

for a ~80% chondrule abundance. As for Asuka-881394 and d'Orbigny, the error is of the order 1 Ma.

4. DISCUSSION

4.1. ^{26}Al-^{53}Mn Ages and Possible Parent-Body Precursors

Our model provides ages of 2.8 ± 1 Ma, 4.3 ± 1.1 Ma for the eucrite Asuka-881394 and the angrite d'Orbigny respectively. These ages are from the agglomeration of the parent-body precursors (CAIs, chondrules, and matrix) to the Al and Mn isotopic closure in the meteorites considered. These ^{26}Al-^{53}Mn ages are constrained within 1 Ma only because we do not know exactly the respective precursors of the eucrite- and the angrite-parent-body. Any progress in the determination of these precursors will provide more precise ages because it will better constrain the range of CAI and chondrule abundances and their chemistry. For now, the important point is that solutions are found for reasonable CAI and chondrule abundances (in the range of a few % and few 10s of % respectively), i.e., similar to the actual chondrite groups.

The chondritic precursors of the eucrite parent-body are not exactly known. Consolmagno and Drake (1977) showed the rare earth element patterns of the HED meteorites can be explained assuming a generic chondritic precursor, but highly depleted in volatiles such as Na and K. An OC parent-body with a a CAI abundance of ~1% and a chondrule abundance of ~70% is a possible solution of our model (Fig. 3). This is close to ordinary chondrites petrology (60–80% chondrules, and <0.1% of CAIs [Scott et al., 1996]). Recent melting experiments have demonstrated that CM chondrites might be plausible precursors of eucrites (Jurewicz et al., 1993). Possible solutions vary between a CM parent-body having 0% CAIs and 70% chondrules and 5% CAIs and 90% chondrules (Fig. 3). These values are different from the real CM chondrites that have 5% CAIs and 20% chondrules (Scott et al., 1996). Note that the chondrule abundance for CM chondrite is the one *after* aqueous alteration.

A recent study of partial melting of the angrite d'Orbigny demonstrated that its parent-body was CV-like (Jurewicz et al., 2004). Looking at the results of our CV model for d'Orbigny, one sees that possible solutions vary between bodies having 0% CAIs and 60% chondrules and 10% CAIs and 70% chondrules. This is not exactly like the actual CV chondrites that have 10% CAIs and 45% chondrules (Scott et al., 1996).

The fact that we do not find exact matches between the eucrite and angrite parent-body chondritic precursors and existing chondrites groups is not problematic, because the chondrites groups that lead, via differentiation to the eucrite and angrite parent-bodies might now be absent from our collections. A good reason for these chondritic precursors to be absent from our current (and biased, see Meibom and Clark, 1999) sampling of the asteroid belt would be because they have

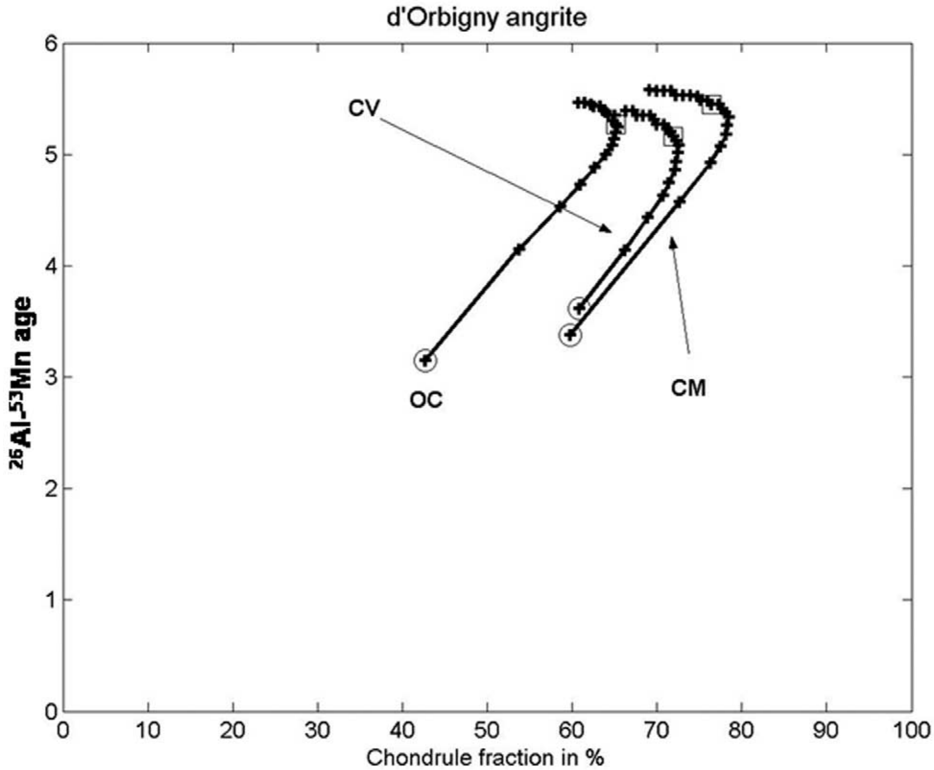

Fig. 4. ^{26}Al-^{53}Mn age plotted vs. the chondrule abundance for the d'Orbigny parent-body for a variety of chemical models (OC, CM, and CV chondrites). This graph is the locus of the solutions of the equation $t_{PB}^{26Al}(\alpha_{CAI},\alpha_C) = t_{PB}^{53Mn}(\alpha_{CAI},\alpha_C)$ for d'Orbigny. Crosses mark the varying abundance of CAIs. They start at 0% (circles), and are plotted every one 1% until 20%. The squares mark the run with 10% CAIs.

formed larger objects that differentiated. Secondary processing, at least for CM chondrites, could also possibly explain the discrepancy between our model solutions and the actual petrography of chondrites groups. The present abundance of chondrules (and CAIs) in CM chondrites has been established after aqueous alteration, whereas our model considers the relative abundance of petrographic components prior to aqueous alteration. Because it is unlikely that aqueous alteration has drastically changed the relative abundance of CM chondrites' petrographic components, we rule out this possibility for explaining the slight discrepancies between our model solution and the actual petrography of chondrites.

The ^{26}Al-^{53}Mn ages identified by our model give the characteristic timescales of the parent-body/meteorite evolution. It means that it took 2.8 $\pm$ 1 Ma for the eucrite parent-body to differentiate and cool since its agglomeration, whereas it took 4.3 $\pm$ 1.1 Ma for the angrite parent-body to differentiate and cool since its agglomeration. The reason for this $\sim$1.5 Ma difference in the evolution of the eucrite and angrite parent-body can be investigated by later petrographic studies. Note that this difference between the eucrite and angrite parent-bodies cooling times could not be identified by a chronology assuming homogeneous distribution of short-lived radionuclides, because such a chronology counts time since the CAI formation, and not since the agglomeration of the precursors which is, in such a framework, an unknown. Similarly, it is worth noting that though allegedly originating from the same parent-body, the two H4 chondrites, Sainte Marguerite and Forest Vale, have significantly different cooling times, 3 and 5 Ma respectively.

To summarise: (1) We have identified ^{26}Al-^{53}Mn ages for a diversity of objects whose ^{26}Al and ^{53}Mn chronology could not be reconciled in the framework of a model assuming an homogeneous distribution of ^{26}Al and ^{53}Mn. (2) The age precision ($\pm$1 Ma) is comparable with that obtained in the model assuming an homogeneous distribution of ^{26}Al and ^{53}Mn in the solar accretion disk, precision being typically around $\pm$2 Ma for the Mn-Cr system and $\pm$0.13 Ma for the Al-Mg system (Nyquist et al., 2003b). (3) These ^{26}Al-^{53}Mn ages are found for chondritic precursors that are realistic, i.e., within the range of petrographic properties of chondrite groups. (4) The slight discrepancies between the solutions of our model and existing chondrite groups are due to the fact that we are so far ignorant of the true chondritic progenitors of angrites and eucrites. (5) The calculated ^{26}Al-^{53}Mn ages give timescales for the evolution of

Table 2. ^{26}Al-^{53}Mn ages (in Ma) found for the d'Orbigny angrite and the Asuka-881394 eucrite for all three chemical models (CM, CV, OC) and for the two extreme CAIs abundances (0 and 10%).

	Asuka-881394		d'Orbigny	
	0% CAIs	10% CAIs	0% CAIs	10% CAIs
CM	1.9	3.8	3.4	5.5
CV	2.0	3.5	3.6	5.2
OC	1.7	3.6	3.2	5.3

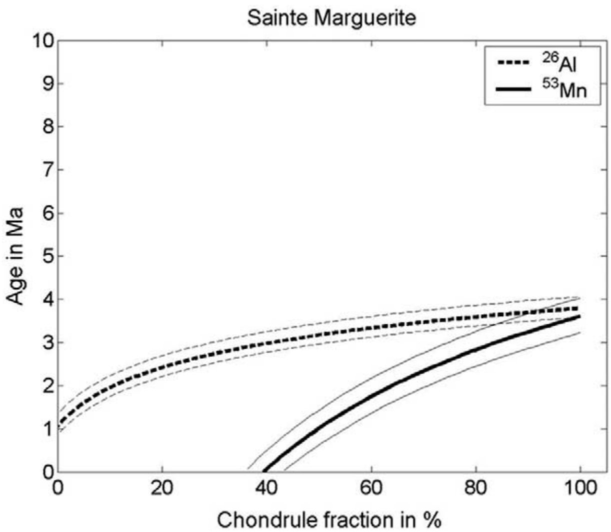

Fig. 5. Aluminium-26 and ^{53}Mn ages for the Sainte Marguerite H4 chondrite. The CAI fraction is taken to be 0.1% (see text), and the OC chemical model has been adopted. The dashed thick line is for ^{26}Al and the continuous thick line for ^{53}Mn. 2σ error bars (that take into account error on the measurement of initial ^{26}Al and ^{53}Mn ratios in Sainte Marguerite, but ignore the model uncertainty on the initial ratio) are shown as thin lines.

the respective parent-bodies/meteorites that can be investigated in the light of further petrographic studies. This last feature is a specificity of our model that counts time since the agglomeration of precursors until the isotopic closure.

4.2. Building an Absolute Chronology

In this section, we try to build an absolute chronology, anchoring our relative ^{26}Al-^{53}Mn chronology to the absolute Pb-Pb and Hf-W chronometer. By absolute, we mean tied to the present time, rather than relative between two early Solar System events. Our calculated ^{26}Al-^{53}Mn age is relative in the sense that it counts the time since the agglomeration of precursors to form a parent-body to the isotopic closure of Al-Mg and Mn-Cr in this parent-body. In the following, we will assume that U isotopes and ^{182}Hf were homogeneously distributed in the solar accretion disk. This is justified by the fact that U isotopes and ^{182}Hf are likely to be the result of continuous galactic nucleosynthesis (Wasserburg et al., 1996), and therefore are expected to be as well mixed as the majority of isotopes that make our Solar System (Birck, 2004).

d'Orbigny has a Pb-Pb age of 4557 $\pm$ 1.5 Ma (Jotter et al., 2003) in agreement with Pb-Pb ages measured previoulsy for other angrites (Lugmair and Galer, 1992). Sainte Marguerite and Forest Vale phosphates have Pb-Pb ages of 4562.7 $\pm$ 0.6 Ma and 4560.9 $\pm$ 0.7 Ma respectively (Göpel et al., 1994). Pb-Pb ages of eucrites have been measured, but they are usually obscured by secondary resetting events (Carlson and Lugmair, 2000). An absolute age can however be calculated for eucrites from their initial ^{182}Hf/^{180}Hf of (7.96 $\pm$ 0.34) $\times$ 10^{-5} ratio measured by Quitté et al. (2000), and using Sainte Marguerite as an anchor because of its precise Pb-Pb and Hf-W ages. With Sainte Marguerite having a Pb-Pb age of 4562.7 $\pm$ 0.6 Ma and an initial ^{182}Hf/^{180}Hf ratio of (8.5 $\pm$ 0.5) $\times$ 10^{-5} (Kleine et al., 2002), we calculate an absolute age for eucrites of 4561.8 $\pm$ 1.1 Ma.

The absolute age for the agglomeration of precursors is the sum between the absolute age of the parent-body and the relative age calculated in section 3.

The absolute ages of d'Orbigny, Asuka-881394, Sainte Marguerite, and Forest Vale, and of the agglomeration of their precursors are plotted in Figure 7 as well as the absolute ages of primitive components (CAIs and chondrules) measured by Amelin et al. (2004). This absolute chronology brings together absolute Pb-Pb ages and calculated ^{26}Al-^{53}Mn ages, providing a coherent Al-Mg/Mn-Cr/Pb-Pb chronology. This can be compared to Figure 6 of Zinner and Göpel (2002), although, once again, the sense of age is different in our model, because we calculate the time of agglomeration of the chondritic precursors of a given parent-body relative to its isotopic closure, rather than the age of isotopic closure relative to CAI formation. Our model provides chronology more internally consistent than the chronology based on an assumption of homogeneity for ^{26}Al and ^{53}Mn (Fig. 1).

The precursors of Forest Vale and Sainte Marguerite are found to have agglomerated at the same time (4565.9 $\pm$ 1.2 Ma and 4565.7 $\pm$ 1.2 Ma, respectively), which was to be expected because these two meteorites are thought to come from the same parent-body. This result could not be obtained with models assuming an homogeneous distribution of ^{26}Al and ^{53}Mn, which can only identify different isotopic closure times for the two meteorites. In addition, the age compatibility for these two meteorites is better than in a model assuming homogeneous distribution of ^{26}Al and ^{53}Mn (Fig. 1). As noted earlier (section 4.1), the question now relevant to the evolution of the H4 parent-body is why the two meteorites have different cooling times.

Our model suggests that eucrite precursors agglomerated

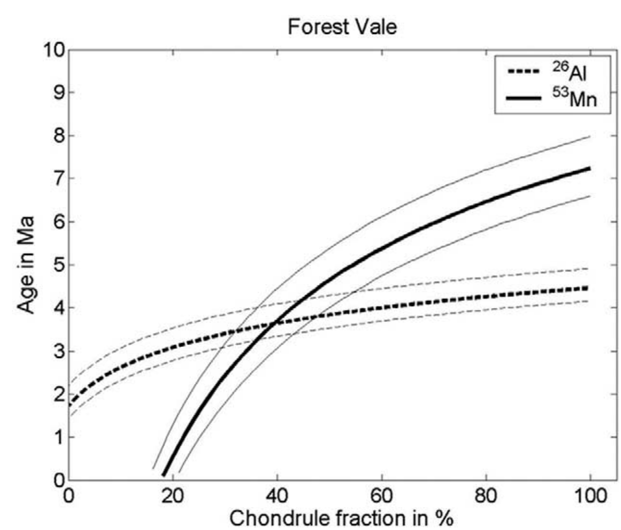

Fig. 6. Aluminium-26 and ^{53}Mn ages for the Forest Vale H4 chondrite. The CAI fraction is taken to be 0.1% (see text), and the OC chemical model has been adopted. The dashed line is for ^{26}Al and the continuous line for ^{53}Mn. 2σ error bars (that take into account error on the measurement of initial ^{26}Al and ^{53}Mn ratios in Forest Vale, but ignore the model uncertainty on the initial ratio) are shown as thin lines.

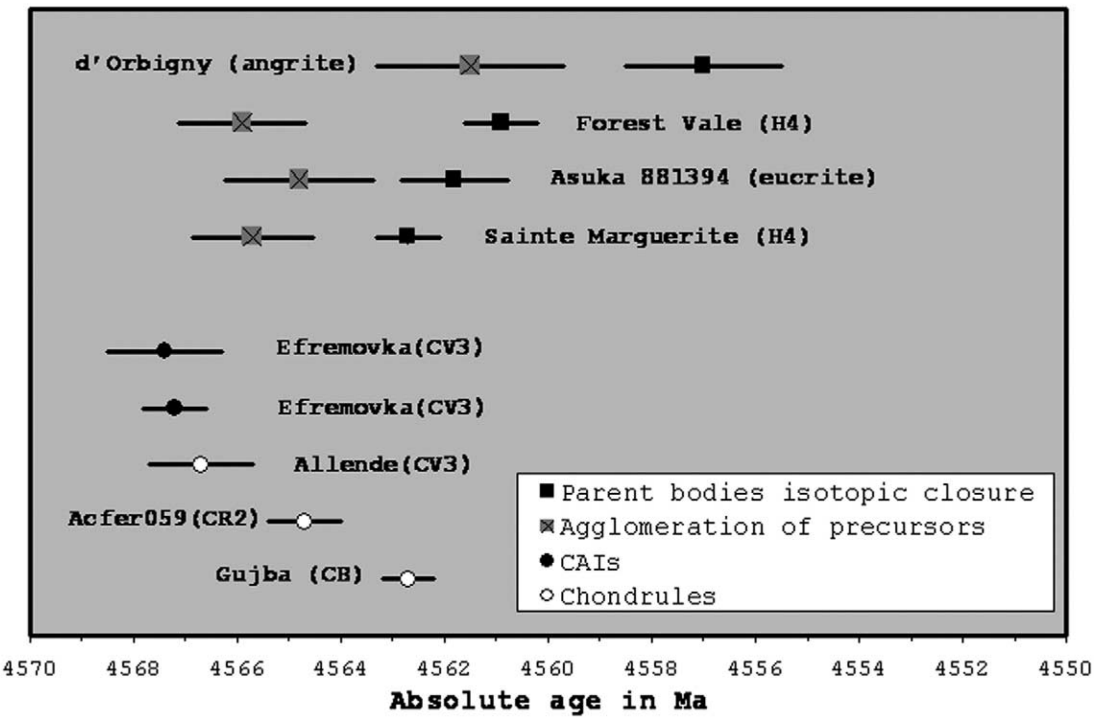

Fig. 7. Absolute timescale for early Solar System events. Black squares denote experimental Pb-Pb ages for D'Orbigny, Forest Vale, and Sainte Marguerite, and a combined Hf-W/Pb-Pb age for Asuka-881394 (see text for references). The gray squares represent the absolute age for the agglomeration of the precursors of d'Orbigny, Asuka-881394, Forest Vale, and Sainte Marguerite. They are the sum of the measured Pb-Pb age of evolved meteorites and of the relative model age of their precursors. Error bars are experimental error bars for the measured Pb-Pb ages, and $\sqrt{\sigma_{exp}^2+\sigma_{calc}^2}$ for the model age, where σ_{exp} is the experimental error on the Pb-Pb age and σ_{calc} the uncertainty on our model given in section 3. The close and open circles are experimental ages for the CAIs and chondrules respectively (Amelin et al., 2002; Amelin et al., 2004).

4564.8 ± 1.4 Ma ago. This is contemporaneous (within errors) with the timing for the agglomeration of OC precursors (4565.8 Ma ago) as determined by our model, and with CV CAIs and chondrule formation measured experimentally (4567.2 ± 0.1 Ma and 4566.7 ± 1.0, respectively). Angrites precursors agglomerated relatively late (4561.5 ± 1.8 Ma ago); this will be discussed in the next section.

If we knew the actual precursors of the considered evolved meteorites, it would be possible to estimate nebular residence timescales for CAIs and chondrules, looking at the differences between the measured Pb-Pb ages for CAIs and chondrules and the calculated ages of the precursors. The fact that the calculated precursors have similar absolute ages to the measured absolute ages of CAIs and chondrules is a comforting result, which gives credit to our assumption (supported by calculations) of short residence times of CAIs and chondrules in the accretion disk.

4.3. Problems Raised by the Absolute Chronology

There are two important consequences, and potential problems, of the absolute chronology shown in Figure 7. First, the absolute calculated age of angrites' precursors is fairly young (4561.5 ± 1.5 Ma). It may be problematic to have the CAI and chondrule formation events lasting as long as 5 Ma or so. Before we discuss the astrophysical situation in more detail, we would like to note that this problem is independent of our chronological model based on an heterogeneous distribution of ^{26}Al and ^{53}Mn. In fact, the only value we calculated is the time between angrites and their precursors (4.3 ± 1.1 Ma), the absolute age of the angrites' precursors being deduced from Pb-Pb data (Jotter et al., 2003). A possibility is that the Pb-Pb age of angrites dates a later event than the crystallisation event recorded by ^{26}Al and ^{53}Mn ages. We discussed above (section 2.1) the assumption of assuming identical isotopic closure for all the radionuclides under scrutiny. The high initial Sr isotopic composition of angrites supports an older age for angrites (Carlson and Lugmair, 2000) than the one inferred from Pb-Pb data.

Second, and independently of the "true" absolute age for angrite, the Pb-Pb data for chondrules may imply that the chondrule formation event might have lasted for ~4 Ma, since "chondrules" from the bencubbinite Gujba formed 4 Ma after CV3 chondrules (Amelin et al., 2004). This conclusion is still tentative because the nature of bencubbinite components is not well understood. Whereas some authors contend that bencubbinites are real chondrites, other believe they have an impact origin (Rubin et al., 2003). Indeed, the "chondrules" in Gujba are centimeter-sized silicate pebbles that may or may not have formed by a similar process to chondrules from other meteorite groups. A long timescale might be a problem for chondrule formation models. For example, in the X-wind model, CAI and chondrule production is linked to the existence of an active accretion disk and a wind (Shu et al., 2001). Active accretion can continue as long as 10 Ma around protostars (Lyo et al., 2003), but the duration of jet activity is less well constrained. Their presence in more evolved objects such as T-Tauri stars is unknown. In the shockwave model (Desch and Connolly Jr., 2002), the persistence of a shockwave source for as long as ~4 Ma might also be problematic.

Another interesting point and potential problem is the requirement of making primitive components (CAIs, chondrules) while differentiated objects already exist (Fig. 7). This problem is linked to the duration of the chondrule forming event exposed above. Because chondrule formation events have been recently shown to have lasted as long as 4 Ma (Amelin et al., 2004), and because many independent lines of evidence indicate that differentiation of many large bodies happened early (e.g., Wadhwa and Russell, 2000), we have to face the question of whether large differentiated bodies can be already present in the disk while chondrules (and CAIs) are still forming.

We note that all the potential problems raised above (late formation of the angrite precursors and long duration of the CAI and chondrule forming events) arise because of the young absolute ages (Pb-Pb) of angrites and Gujba chondrules, and are independent of our model.

4.4. Model Compatibility with Other ^{26}Al and ^{53}Mn Data

Our model tries to build a coherent ^{26}Al-^{53}Mn relative chronology. As such, it is inappropriate to deal with objects for which one aspect of the data (^{26}Al or ^{53}Mn) is missing. There are, however, a few objects that have yielded important results possibly contradictory with our model and, as such, deserve discussion.

Carbonates in aqueously altered chondrites (petrographic type $\leq$2) contained ^{53}Mn at a high level when they stopped interacting with asteroidal water. This is true of Orgueil and Ivuna (Endress et al., 1996), but also of CM chondrites (Brearley and Hutcheon, 2000). The highest ratios have been found in the CM2 chondrite Y791198, $^{53}\text{Mn}/^{55}\text{Mn} = (1.31 \pm 0.60) \times 10^{-5}$ (Brearley and Hutcheon, 2002), and in the Kaidun breccia, $^{53}\text{Mn}/^{55}\text{Mn} = (0.94 \pm 0.16) \times 10^{-5}$ (Hutcheon et al., 1999). These high initial ^{53}Mn values signify an early aqueous alteration activity on some of the carbonaceous chondrite parent-bodies. The exact timing of this alteration obviously depends on the Solar System initial ^{53}Mn/^{55}Mn, in the context of a model where short-lived radionuclides are homogeneously distributed in the solar accretion disk, and on the initial ^{53}Mn/^{55}Mn ratio of the precursor parent-body in the context of our model.

In our model, the ^{53}Mn content of carbonates would date the timing of alteration since the agglomeration of the parent-body. The calculated initial ^{53}Mn/^{55}Mn of our CM model varies with chondrule and CAI content (see Eqn. 1). Because of the very low amount of Mn present in CAIs (Table 1), most of the ^{53}Mn present in any parent-body originates from chondrules, and the initial ^{53}Mn/^{55}Mn of a CM parent-body is virtually independent of the CAI-fraction (see below, section 4.5 and Fig. 8b). The initial ^{53}Mn/^{55}Mn of a CM parent-body varies from $\sim 0.2 \times 10^{-5}$ for a chondrule content of 20% to $\sim 0.94 \times 10^{-5}$ for a chondrule content of 100%. For a CM2 parent-body having 70% or more chondrules, this initial ^{53}Mn/^{55}Mn ratio ($\sim 7 \times 10^{-6}$) is compatible within errors with the measured value in the CM2 carbonates ($^{53}\text{Mn}/^{55}\text{Mn} \leq (1.31 \pm 0.60) \times 10^{-5}$).

Another related problem is the compatibility of our model with the measurements of carbonaceous chondrites (Birck et al., 1999; Rotaru et al., 1992). Birck et al. (1999) showed that the CI parent-body formed with an initial $^{53}\text{Mn}/^{55}\text{Mn} = (2.04 \pm 0.33) \times 10^{-5}$, a value once again higher than any of our calculated initial ^{53}Mn/^{55}Mn ratios. The problem also applies to CM2 chondrites [$^{53}\text{Mn}/^{55}\text{Mn} = (1.14 \pm 0.33) \times 10^{-5}$; Birck et al., 1999]. Manganese-53 to manganese-55 initial ratios of carbonaceous chondrite whole rocks and carbonates seem to indicate that our model faces a problem of a general nature for carbonaceous chondrites.

A possible solution to this problem is to come back to one of our input parameters, the initial ^{53}Mn/^{55}Mn ratio of carbonaceous chondrite chondrules. We have adopted, in absence of measurements for the initial ^{53}Mn/^{55}Mn ratio of carbonaceous chondrite chondrules, the value of ordinary chondrite chondrules, $^{53}\text{Mn}/^{55}\text{Mn} = 9.4 \times 10^{-6}$. If carbonaceous chondrite chondrules had a higher ^{53}Mn/^{55}Mn ratio of $2\text{–}3 \times 10^{-5}$, all the aforementioned problems would be solved. Indeed, if the ^{53}Mn/^{55}Mn initial ratio of carbonaceous chondrite chondrules was equal to $\sim 2.5 \times 10^{-5}$, a CM parent-body with 40% chondrules would have an initial ^{53}Mn/^{55}Mn ratio of $\sim 1 \times 10^{-5}$, compatible with the initial ratio found by Birck et al. (1999), and with the initial ^{53}Mn/^{55}Mn ratio of carbonates. The initial ^{53}Mn/^{55}Mn of the CI chondrite parent-body would be easily reproduced by a parent-body having ~80% chondrules. We also note that, if the initial ^{53}Mn/^{55}Mn ratio of carbonaceous chondrites chondrules was higher than ordinary chondrite chondrules, it would also solve the problem of selecting CM or CV precursors for angrites and eucrites having high chondrule contents (see section 4.1). Indeed, if more ^{53}Mn was initially present within chondrules, one needs fewer chondrules to achieve a given ^{53}Mn/^{55}Mn ratio, i.e., a given age (see Fig. 8d). We expect a significantly higher initial ^{53}Mn/^{55}Mn ratio to be measured in carbonaceous chondrites chondrules than in ordinary chondrite chondrules.

4.5. Sensitivity of the Model to Input Parameters

Changing the initial ^{53}Mn/^{55}Mn ratio of chondrules modifies the chondrule abundance needed to yield a given ^{26}Al-^{53}Mn age (section 4.4 and Fig. 8d). What about changing other input parameters? In other words, how robust is our model? In Figures 3 and 4, one can appreciate the sensitivity of our model to the chemical composition of chondrules, CAIs, and matrix (C_i of Eqn. 1) because we show different chemical models (CM, OC, CV). As already discussed, ^{26}Al-^{53}Mn ages depend little on the assumed chemical composition of the precursors. The next input parameters we need to examine are the initial ^{26}Al and ^{53}Mn content of CAIs and chondrules.

The model is insensitive to the initial ^{53}Mn/^{55}Mn ratio of CAIs (Fig. 8b). This is because there is little Mn in CAIs (Table 1), and therefore CAIs do not contribute significantly to the mass balance of ^{53}Mn in the precursor parent-body (see Eqn. 1). Similarly, because Al is concentrated in CAIs rather than in chondrules, and because the ^{26}Al of CAIs is larger than that of chondrules (Table 1), essentially all of the initial ^{26}Al of the

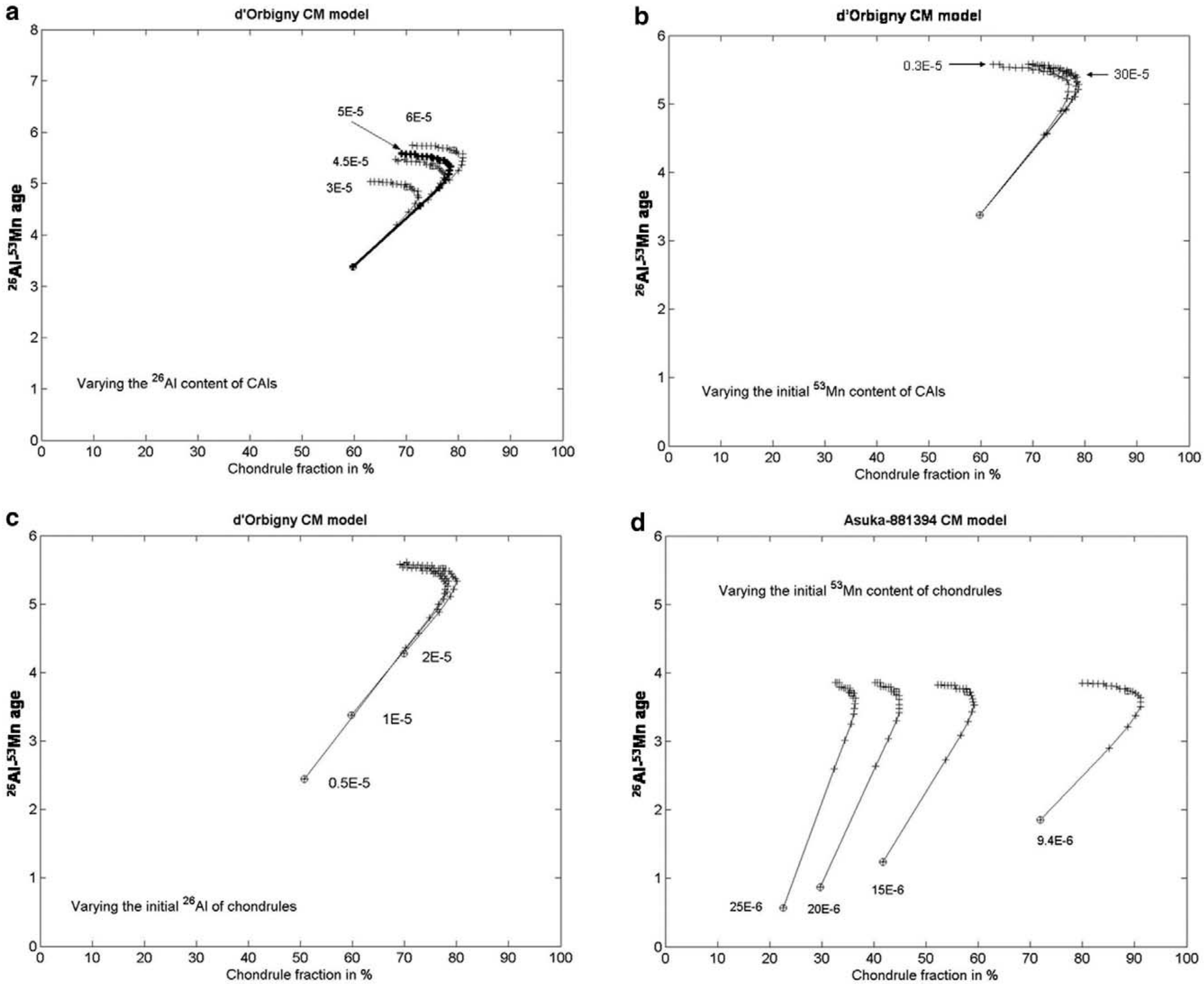

Fig. 8. ^{26}Al-^{53}Mn age calculated using varying parameters for the model. A CM model has been adopted throughout. Only one variable is changed in each panel. (a) Effect of varying the initial ^{26}Al/^{27}Al ratio of CAIs from 3 to 6 $\times$ 10^{-5}. (b) Effect of varying the initial ^{53}Mn/^{55}Mn ratio of CAIs from 0.3 to 30 $\times$ 10^{-5}. Specifically, it makes no difference to our model if the initial CAI ratio ^{53}Mn/^{55}Mn is 1 $\times$ 10^{-5} or 3 $\times$ 10^{-5}. (c) Effect of varying the initial ^{26}Al/^{27}Al of chondrules from 0.5 to 2 $\times$ 10^{-5}. (d) Effect of varying the initial ^{53}Mn/^{55}Mn ratio of chondrules from 9.4 to 25 $\times$ 10^{-6}.

parent-body originates from CAIs. Apart from parent-bodies having originally no CAIs, the results of our model are insensitive to the adopted ^{26}Al ratio of chondrules—as long as it is not comparable to the initial ^{26}Al of CAIs (Fig. 8c). Our model depends quite strongly on the initial ^{26}Al/^{27}Al ratio of CAIs (Fig. 8a), which is well constrained. The canonical ratio of 5 $\times$ 10^{-5} we adopted has been established by decades of measurements (MacPherson et al., 1995). Variations of 10% around it would not significantly change the ages we calculated (Fig. 8a), especially if the ^{26}Al content of CAIs is revised upwards, as might be the case (Galy et al., 2004). We have already discussed above how our model depends on the initial ^{53}Mn/^{55}Mn ratio of chondrules. In this case, we also adopted the measured values at our disposal, and in addition speculated that the initial ^{53}Mn/^{55}Mn ratio of carbonaceous chondrites chondrules should be higher than the initial ^{53}Mn/^{55}Mn ratio of ordinary chondrites chondrules.

Our model therefore depends only strongly on the initial ^{26}Al content of CAIs and of the initial ^{53}Mn content of chondrules. With the exception of the initial ^{53}Mn content of carbonaceous chondrite chondrules, both values are well constrained from experimental data. The reason for this fact is that our model is a simple mixing model, and that in a precursor parent-body, most of the ^{26}Al is borne by CAIs, and most of the ^{53}Mn is borne by chondrules. In writing the elementary Eqns. 1 and 2, the only change we make compared to traditional chronological models is to change the initial ^{26}Al and ^{53}Mn initial ratios by diluting them. This is a simple way to solve the long known paradox of the high initial value of ^{53}Mn in CAIs (Lugmair and Shukolyukov, 1998, 2001).

To summarise, after examination of all the input data, our model appears robust to any reasonable change of the input data.

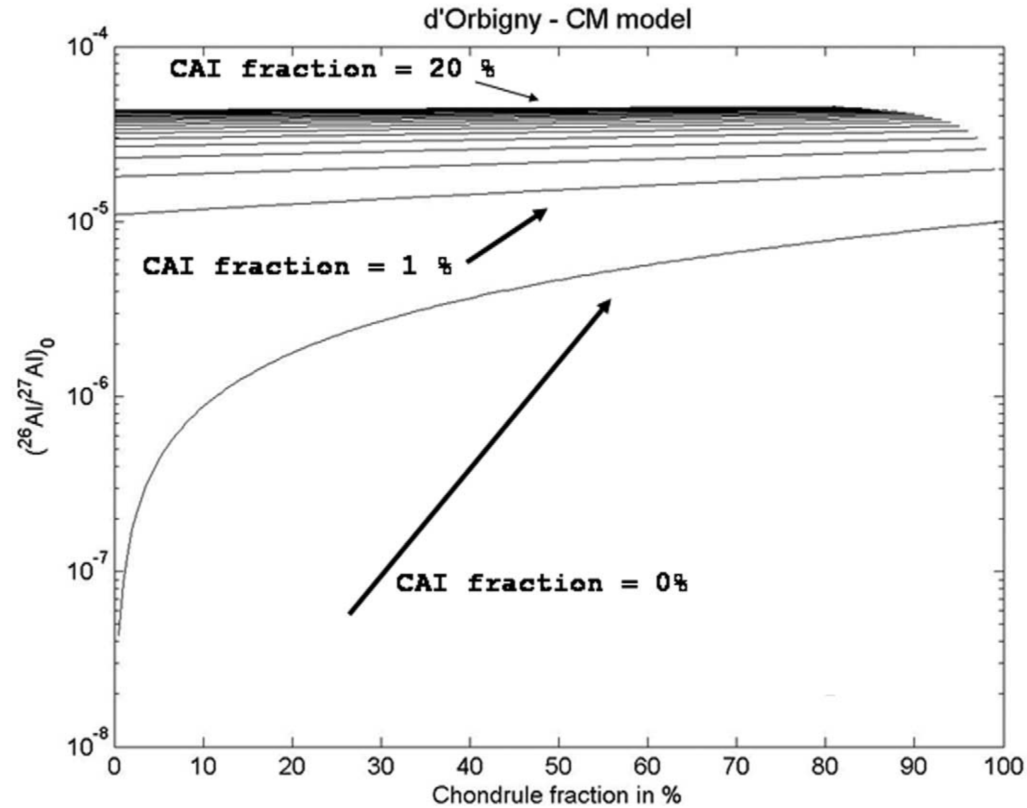

Fig. 9. Initial $^{26}Al/^{27}Al$ ratios as a function of CAI and chondrule abundances for the d'Orbigny parent-body assuming an initial CM chemistry. The high initial content of ^{26}Al demonstrates that this short-lived radionuclide is a potential heat source to melt asteroids.

4.6. Heating of Asteroids

Aluminium-26 is a gamma emitter, and has long been proposed to be the heating source of asteroids (Urey, 1957). Many workers have developed models of asteroid heating based on the energy released by ^{26}Al (e.g., Bennett III and McSween Jr., 1996; Ghosh and McSween Jr., 1998; Grimm and McSween Jr., 1993). It is however only recently that the important effect of accretion has been taken into account (Ghosh et al., 2003; Merk et al., 2002). Because thermal models yield already a wide spectrum of evolutionary possibilities (Ghosh et al., 2003), modifications in the ^{26}Al initial content of parent-bodies in our model will not bring very different outcomes, but might open wider possibilities. The goal of this section is to show that our model does not jeopardize the potential of ^{26}Al as a heat source, i.e., that the initial ^{26}Al content in our parent-bodies is sufficient for melting large asteroids.

In Figure 9 we show the initial ^{26}Al content of the d'Orbigny parent-body as a function of the chondrule fraction and of the CAI fraction. Excluding the case with 0% CAIs, one can see that the initial $^{26}Al/^{27}Al$ content is at least $\sim 10^{-5}$, and typically a few 10^{-5}. Comparing our data to that of Ghosh et al. (2003), it means that our calculated $^{26}Al/^{27}Al$ at the starting time of accretion (their T_{INIT}) is equal to a few $\times$ 10^{-5}. This is compatible with the Ghosh et al. (2003) model that explores a range of initial $^{26}Al/^{27}Al$ from 2.5×10^{-5} to 2.5×10^{-6} (see Table 1 of Ghosh et al., 2003).

In general, the initial $^{26}Al/^{27}Al$ ratio of the parent-body in our model can potentially be higher than in any model that assumes ^{26}Al was homogeneously distributed in the solar accretion disk, and that chondrules formed a few Ma after CAIs. In such models, the highest possible initial $^{26}Al/^{27}Al$ ratio is that of the chondrules with the highest recorded $(^{26}Al/^{27}Al)_0$, i.e., $<1 \times 10^{-5}$. In our model, it can be as high as a few $\times 10^{-5}$ (Fig. 9). Our model can therefore potentially overcome problems met by other models that have too little ^{26}Al to melt asteroids (Kunihiro et al., 2004).

5. CONCLUSIONS

We have developed a model of early Solar System chronology, based on an assumption of heterogeneous distribution of ^{26}Al and ^{53}Mn. In this model, all evolved bodies are supposed to be originally chondritic, i.e., to be made of a mixture of CAIs, chondrules, and matrix. This mixture determines the initial content in ^{26}Al and ^{53}Mn of a chondritic parent-body as a function of its CAI and chondrule abundance fraction. This approach enables us to calculate ^{26}Al-^{53}Mn ages since the agglomeration of the parent-body precursors until the isotopic closure of the Al-Mg and Mn-Cr systems.

The age since agglomeration of precursors of the d'Orbigny angrite is 4.3 $\pm$ 1.1 Myr, for the Asuka-881394 eucrite 2.8 $\pm$ 1.0 Myr, for the H4 chondrite Sainte Marguerite $\sim$3 Myr, and for H4 Forest Vale $\sim$5 Myr. These ^{26}Al-^{53}Mn ages are found for realistic precursors, i.e., objects having similar or identical petrography to the existing chondrite groups. The slight differences between the petrography of the calculated respective chondritic precursors of the angrite and eucrite parent-bodies and the actual chondrites is not a problem, because there is no reason for the true chondritic precursors of eucrites and angrites to be within the (biased) present sampling of the asteroid belt. The calculated ^{26}Al-^{53}Mn ages give timescales for the evolution of the respective parent-bodies/meteorites that can be investigated in the light of further petrographic studies. For example, it might be possible to identify petrographic motives for which the angrite parent-body took longer to cool than its eucrite counterpart. This possibility of measuring the evolution time of a given asteroid is not doable with a model assuming an homogeneous distribution of short-lived radionuclides.

We anchor the calculated relative chronology to an absolute chronology (Fig. 7) using absolute Pb-Pb ages and relative Hf-W ages (for eucrites) of the objects under scrutiny. Our model provides a fully compatible Al-Mg/Mn-Cr/Pb-Pb chronology, and is shown to be robust to any reasonable change in the input parameters. We showed that the precursors of Sainte Marguerite and Forest Vale agglomerated at the same time ($\sim$ 4565.8 $\pm$ 1.2 Ma ago), which is coherent with the idea that these two H4 chondrites come from the same parent-body. The precursors of eucrites (Asuka-881394) agglomerated 4564.8 $\pm$ 1.2 Ma ago, at a time when CAIs and chondrules from CV3 and CR2 chondrules were forming. The precursors of angrites agglomerated late (4561.5 $\pm$ 1.8 Ma ago). This late agglomeration arises from a recent Pb-Pb age and not from our model.

Because the initial ^{26}Al/^{27}Al initial ratio of the parent-body under consideration results from the mixing of phases with high ^{26}Al content (CAIs) and phases with low ^{26}Al content (chondrules), the net initial ^{26}Al content is higher than in models that agglomerate parent-bodies after a 2 Ma delay, when the ^{26}Al is that of chondrules. Our model therefore provides ample ground for the heating of asteroids by ^{26}Al decay.

We would like to note that, beyond the actual age figures we propose, what matters is our radical change in approach. (1) Ages do not have the same meaning as in other models, because they count the time elapsed from the agglomeration of the parent-body precursors to the isotopic closure of ^{26}Al and ^{53}Mn. (2) It is not possible in our model to date age differences between CAIs and chondrules using ^{26}Al and ^{53}Mn. (3) Not all CAIs formed contemporaneously, and so their age cannot be used as a start point for the solar system. On the other hand, the present model makes it possible (1) to build an internally consistent Al-Mg/Mn-Cr/Pb-Pb chronology, (2) to date the evolution timescale of asteroids since their agglomeration to isotopic closure.

Our model makes certain specific predictions, including that when measured, CAIs from CR chondrites should have the same Pb-Pb age as chondrules from CR chondrites. Carbonaceous chondrite chondrules could have a higher ^{53}Mn/^{55}Mn initial ratio than ordinary chondrite chondrules. Undoubtedtly, the most convincing test will be to apply it to a new short-lived radionuclide that might have been heterogeneously distributed in the Solar System, like ^{10}Be. Perhaps the best test of our model will be measurements of ^{10}Be within chondrules and evolved objects.

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