CONSTRAINTS ON THE ORIGIN OF CHONDRULES AND CAIS FROM SHORT-LIVED AND LONG-LIVED RADIONUCLIDES.

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Introduction: In order to understand the timing of events in the early solar system, we rely on the radio-nuclide-based chronometers applied to materials in primitive meteorites. Because the time scale of early-solar system evolution was on the order of a few million years (Myr), we focus on so-called "short-lived radionuclides" with mean lives of less than 10 Myr (Table 1), as well as on the long-lived U-Pb system where high precision ^{207}Pb-^{206}Pb ages are applied. Note that the validity of some systems as chronometers (e.g., Be-B, Fe-Ni) has yet to be established. We summarize literature data for chondrules and CAIs and discuss how these chronometers constrain formation time scales in the early solar system.

Table 1. Short-lived nuclides for early solar system chronometry

Parent nuclide	Daughter nuclide	τ_{half} (Myr)	Initial abundance
^{41}Ca	^{41}K	0.1	^{41}Ca/^{40}Ca ~ 2E-8
^{26}Al	^{26}Mg	0.73	^{26}Al/^{27}Al ~ 5E-5
^{10}Be	^{10}B	1.5	^{10}Be/^{9}Be~ 1E-3
^{60}Fe	^{60}Ni	1.5	^{60}Fe/^{56}Fe~ 5E-7?
^{53}Mn	^{53}Cr	3.7	^{53}Mn/^{55}Mn~ 1E-5?

The initial abundances of short-lived nuclides in primitive meteoritic materials are determined from analyses of the excesses of daughter nuclides correlated with the stable isotope of the parent element. By assuming a homogeneous distribution of short-lived nuclides in the early solar system, variations in the estimated isotope ratios (R) can be transferred to relative ages as follows;

$$\Delta t = \ln\left(R/R_0\right) \times \tau_{half} / \ln(2) \; ,$$

where R_0 represents the solar system initial isotope ratio for a specific short-lived nuclide (values listed in Table 1).

The ^{26}Al-^{26}Mg system: Since the discovery of ^{26}Mg excesses, correlated with Al/Mg ratios, in CAIs confirmed the former-existence of live-^{26}Al in the early solar system [1], numerous data have been obtained for CAIs, chondrules, and plagioclase in both equilibrated ordinary chondrites (EOC) and achondrites. These data (summarized in Fig. 1) indicate (1) the majority of CAIs formed contemporaneously within a short time interval of no more than a few hundred thousand years, (2) chondrule formation began 1-2 Ma after CAI formation and persisted for ~1-3 Myr; and (3) plagioclases in EOC and achondrites processed in parent bodies are at least 4-5 Myr younger than CAIs. These time scales are comparable to those of classes I, II, and III young stars inferred on the basis of infrared observations; (1) ~0.1 Myr for Proto-stars, (2) ~3 Myr for classical T-Tauri stars, and (3) ~10 Myr for weak-lined T-Tauri stars [2]. The ^{26}Al-^{26}Mg chronometer is thus most plausibly interpreted in terms of sequential chain of events – CAIs formed first in the earliest active solar nebula, chondrules next in the quasi-steady proto-planetary disk, and planetary accretion then started a few Myr after the formation of the solar system.

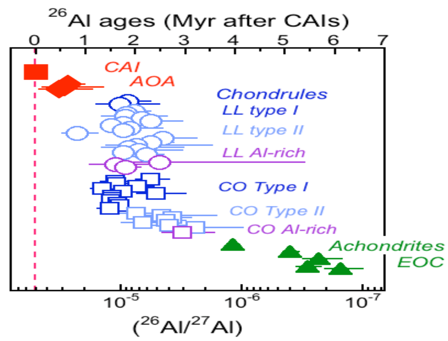

Fig. 1. Summary of ^{26}Al ages from CAIs, chondrules and other meteorites. The initial ^{26}Al/^{27}Al ratios of well correlated isocrhons obtained from CAIs distributed mostly between (4-6) $\times 10^{-5}$ [3]. Other data for individual samples are from [4-16].

Systematic studies of chondrules in LL3.0-3.1 and CO3.0 chondrites indicate contemporary formation in spite of the fact that they formed in distinct isotopic and chemical reservoirs. Chondrules in LL3.0-3.1 show a correlation of the ^{26}Al-^{26}Mg age with bulk Si/Mg and abundances of volatiles, implying that the chemical compositions of chondrule precursors evolved with time from more refractory compositions to volatile ones [10, 17]. Data from CO3.0 chondrites show the tendency that FeO-rich type II chondrules are relatively younger than FeO-poor type I chondrules [11-12].

The high precision Pb-Pb ages: High precision Pb-Pb absolute ages were recently obtained for CAIs and chondrules, after repeated leaching steps to remove non-radiogenic Pb [18]. The average of two CAIs in Efremovka gave the oldest Pb-Pb age of 4567.2±0.6 Myr, while multiple chondrule data from Acfer059 gave the age of 4564.7±0.6 Myr. Thus, these data confirm an ~2 Myr time difference between CAIs and chondrules. Further studies for chondrules from various meteorites are being conducted.

Coherence of the short-lived chronometers: In theory, if the solar system was homogenized, it should be possible to infer the same chronology from any of the various long- and short-lived isotopic chronometers. The various chronometers based on short-lived radionuclides do give approximately the same overall time scale and put the various events in approximately the same order (e.g, Fig. 2), but in detail, there are significant disagreements. Many of these disagreements probably reflect isotopic disturbance of one or more of the systems. Some of them are disturbed or reset very easily. In addition, the nebula may not have been fully homogeneous (cf, the Mn-Cr system [20-22]). In spite of these complications, several systems show that CAIs are the oldest solids, chondrule began to form ~1 Ma later, and meteorite metamorphism and asteroid differentiation required an additional few Ma (Fig. 2)

Constraints from other nuclides: High and variable abundance of the $^{10}Be/^{9}Be$ (5-10×10^{-4} [23-25]) inferred from ^{10}B excesses in CAIs requires the production of this short-lived nuclide by high-energy particle irradiation. It has been suggested that CAIs formed closed to the sun where production of ^{10}Be was sufficient, although the contribution of particle irradiation to the other short-lived nuclides, such as ^{26}Al, is considered to be small [25]. Recently, ^{60}Ni excesses from decay of ^{60}Fe were observed in troilite and a radial pyroxene chondrule in UOCs, indicating the initial $^{60}Fe/^{56}Fe$ of the solar system to be 3×10^{-7} or higher [26-28]. This level of ^{60}Fe may require a supernova source that injected other short-lived nuclides into the Sun's parent molecular cloud as well and may have triggered the formation of the solar system.

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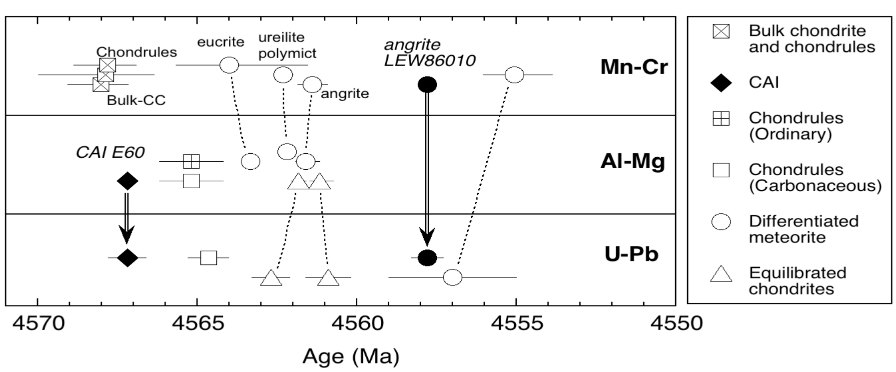

Fig. 2. Comparison of three chronometers. The ^{26}Al and ^{53}Mn ages are converted to absolute ages by using CAIs (4567.2Ma [18]) and LEW86010 (4557.8Ma [19]) as references, respectively.