AN APPRAISAL OF ^{207}Pb-^{206}Pb AND ^{26}Al-^{26}Mg CHRONOLOGIES IN CAIs AND CHONDRULES. A. Bouvier and M. Wadhwa, School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 85287, USA. Email: Audrey.Bouvier@asu.edu.

Introduction: Precise and accurate radiometric dating of chondrites and their components (CAIs, chondrules and matrix minerals) sheds light on the processes and timescales for events occurring in the protoplanetary disk. Analytical improvements associated with new laboratory procedures (i.e., ultra-low blanks, high yields) and mass spectrometry (MC-ICPMS, TIMS, SIMS) over the last decade have extended dramatically the capabilities for obtaining ages with high (typically, sub-My) precision with both long-lived (e.g., ^{207}Pb-^{206}Pb) and extinct (e.g., ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, ^{182}Hf-^{182}W) isotopic systems. While many precise and concordant dates have been obtained by using different clocks on similar objects, there are also some discrepancies [1]. Some possible explanations for such discrepancies may be as follows: (i) the parent radionuclide may not have been homogeneously distributed in the meteorite-forming region of the protoplanetary disk; (ii) the chronometers under consideration may have distinctly different closure temperatures such that some chronometers may have closed at resolvably different times than others in the same sample; (iii) secondary processes, such as thermal and/or shock metamorphism and aqueous alteration, may have disturbed the isotopic systematics to different degrees; (iv) uncertainties in the initial isotopic composition of the daughter element and in the decay constant may also introduce some discrepancies between high-resolution chronometers.

In the following we provide an appraisal of the high-resolution ages of CAIs and chondrules provided by the ^{207}Pb-^{206}Pb and ^{26}Al-^{26}Mg chronometers. In particular, we discuss some of the discrepancies that currently exist and how these may be resolved in the future.

CAI and chondrule dating: Some of the most important issues in cosmochronology relate to the age of the Solar System (estimated from the formation age of the oldest known solids, the CAIs) and the timescales of events occurring in the protoplanetary disk (estimated from the formation ages of chondrules).

While some of the extinct chronometers yield model ages as old as 4568 to 4570 Ma for the start of the Solar System [2-4], the first precise Pb-Pb age from two inclusions from the CV3 chondrite Efremovka gave a somewhat younger age of 4567.2 ± 0.6 Ma, recently revised to 4567.1 ± 0.2 Ma [5, 6]. New Pb isotope analyses of CV3 Allende CAIs, considered along with previous results for the Efremovka E60 inclusion [5], give an absolute age of 4568.5 ± 0.5 Ma for CAI formation [7]. There is therefore an apparent discordance of ~1.4 My between the estimates of Amelin [6] and Bouvier et al. [7] for the formation age of CAIs. In contrast, Al-Mg chronometry gives a relatively short time interval for CAI formation (i.e., on the order of a few 10s of Ky [8, 9]).

Most previous studies of Al-Mg systematics in chondrules of unequilibrated chondrites indicate that these were formed ~1-3 My after CAIs [10]. Nevertheless, Al-Mg model ages of bulk chondrules may indicate that chondrule formation may have begun contemporaneously with CAI formation [11]. Pb-Pb ages obtained thus far for chondrules vary from ~4567 to 4562 Ma [5, 12, 13], with the youngest age (for chondrules from the Gujba CB chondrite) possibly reflecting formation during impact between planetary embryos [13].

Pb-Pb systematics. The most precise CAI age of 4567.1 ± 0.2 Ma was obtained from radiogenic fractions of E60 (a forsterite-bearing type-2 CAI) with the highest measured ^{206}Pb/^{204}Pb ~2260 [6]. Such radiogenic Pb isotopic compositions were obtained by utilizating an extensive leaching procedure to remove terrestrial and chondritic common Pb. Small amounts of Pb (50-500 picograms) in the most radiogenic fractions were measured using the double-spike technique by TIMS [6]. However, since Efremovka is thought to have experienced a severe shock history [14], it is possible that the U-Pb system in some of the E60 fractions may have been affected by shock metamorphism.

The CAI age of Bouvier et al. [7] was obtained by isotope analyses of Pb (5-8 nanograms) in Allende CAI fractions by MC-ICPMS using the Tl doping method to correct for mass fractionation [15]. This study reported less radiogenic isotope compositions (^{206}Pb/^{204}Pb ~59-80) due to a milder leaching procedure employed (to avoid differential dissolution of CAI phases). The best estimate of the CAI formation age of 4568.5 ± 0.5 Ma in this study was obtained by considering the three Allende CAI fractions [7] along with the seven clear and white fragments of the Efremovka E60 (with ^{207}Pb*/^{206}Pb* ages between ~4567.2 and ~4569.0 Ma) [5]. This is consistent with the Hf-W age of Allende CAIs [4] and with model ages of Solar System formation from other extinct chronometers.

It is clearly important in Pb isotope analyses of CAIs to remove as much of the common Pb component as possible so as to minimize the uncertainties resulting from the subtraction of an assumed common Pb composition [16]. Nevertheless, the assumption that there is no isotope fractionation during leaching needs to be more rigorously evaluated, and we plan to test this with further experiments. Furthermore, it is also recognized that the CAIs analyzed thus far are from chondrites (i.e., Efremovka and Allende) that have experienced a complex secondary alteration history. It will therefore be important to analyze CAIs from other primitive chondrites that are less severely affected by such secondary processing.

Al-Mg systematics. While it has been demonstrated that there were Cr and Ni isotopic heterogeneities in the protoplanetary disk which may complicate the interpretation of ages obtained from the ^{53}Mn-^{53}Cr and ^{60}Fe-^{60}Ni short-lived chronometers [17, 18], the ^{26}Al-^{26}Mg system appears to be free from such complications and there is evidence that ^{26}Al was homogeneously distributed in the meteorite-forming region of the protoplanetary disk [8]. However, estimations of the timescales over which CAIs and chondrules were formed are dependant of the initial value of ^{26}Al/^{27}Al for the Solar System, and this issue is currently under debate. Until recently, the best estimate for the initial ^{26}Al/^{27}Al ratio for the Solar System was the canonical value of $\sim 5 \times 10^{-5}$ [19]. However, more recent (high precision MC-ICPMS and SIMS) analyses indicate that this value may be higher (i.e., $\sim 6 \times 10^{-5}$; [8, 9, 20]). It is possible that the higher initial value may represent the value for the solar system at the time of Al/Mg fractionation in CAI precursor materials, whereas the near-canonical value (commonly obtained from mineral phases within CAIs by SIMS) could represent the value at the time of isotopic closure of the Al-Mg system in CAIs. However, such an explanation may be problematic given more recently reported results. Specifically, MC-ICPMS analyses of microdrilled samples of CAIs (fine-grained and igneous) from four carbonaceous chondrites yielded a highly precise initial ^{26}Al/^{27}Al ratio of $(5.85 \pm 0.05) \times 10^{-5}$ [8]. However, more recent analyses of fragments of Allende CAIs (also by MC-ICPMS) gave an initial ^{26}Al/^{27}Al ratio of $(4.90 \pm 0.28) \times 10^{-5}$, similar to the earlier canonical value [21]. While it is possible that sampling issues (i.e, whether the samples being analyzed represent true "bulk" compositions or if they are dominated by a particular mineral phase) may be the cause of this apparent discrepancy, it is clear than this cannot be resolved without further high-precision analyses of well-characterized CAIs (bulk samples and clean individual mineral phases) from relatively pristine primitive chondrites.

Conclusion: ^{207}Pb-^{206}Pb and ^{26}Al-^{26}Mg chronometers in CAIs and chondrules show a number of inconsistencies that need further investigation. These will be addressed with future high-precision analyses of both Pb-Pb and Al-Mg isotope systematics in the same bulk samples and mineral separates from CAIs and chondrules separated from primitive chondrites with minimal secondary alteration.

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