TOWARD CONSISTENT CHRONOLOGY IN THE EARLY SOLAR SYSTEM: HIGH RESOLUTION $^{53}\text{Mn}^{-53}\text{Cr}$ CHRONOMETRY APPLIED TO CHONDULES IN PRIMITIVE ORDINARY CHONDRITE.

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Introduction: The use of short-lived radio nuclides as robust high-resolution chronometers in the early Solar System is based on the fundamental assumption that all these radio nuclides were initially homogeneously distributed throughout the early solar nebula. This assumption can be rigorously tested by cross calibrating the different chronometers through acquisition of high-precision isotope data in a suite of early solar system materials suitable for this purpose. Classically, the short-lived $^{53}\text{Mn}^{-53}\text{Cr}$ chronometer ($T_{1/2}=3.7$ Ma) is anchored to the absolute Pb-Pb age of 4557.8±0.5 Ma [1] for angrites LEW 86010 (LEW) and Angra dos Reis (ADOR) with the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio of $(1.25±0.07)x10^{-6}$ [2]. A growing number of new high-precision data suggests that short lived relative chronometers such as the $^{26}\text{Al}^{-26}\text{Mg}$ system ($T_{1/2}=0.73$ Ma) are broadly consistent with the high-precision long-lived $^{207}\text{Pb}^{-206}\text{Pb}$ chronometer (see [3]). It has been recognized for some time, however, that there are some inconsistencies in the $^{53}\text{Mn}^{-53}\text{Cr}$ chronometry (cf. [4]). For example, when using the angrite age anchor of [3] based on the $^{53}\text{Mn}^{-55}\text{Mn}$ ratios, the chondrules of ordinary chondrites [5] are older than that of CAIs, the oldest known solid objects of our solar system [6]. This is opposite to what one would conclude based on $^{26}\text{Al}^{-26}\text{Mg}$ and U-Pb chronometers, where most chondrules appear to be ≈2 Ma younger than the CAIs (cf. [7] for a recent review). Such results could be interpreted prematurely as an argument against a chronological interpretation for short-lived radioactivity in the early solar system and instead as favoring arguments for production of $^{53}\text{Mn}$ within the solar nebula and/or heterogeneous distribution of $^{53}\text{Mn}$ and $^{26}\text{Al}$ within the early solar system. The importance of this problem prompted us to revisit this issue using MC-ICP-MS to obtain high-precision $^{53}\text{Mn}^{-53}\text{Cr}$ data in a suite of chondrules from a primitive ordinary chondrite, Chainpur (LL3.4).

New results from UC Davis: Our new results show that the initial $^{53}\text{Mn}^{-55}\text{Mn}$ in Chainpur chondrules is $(5.1±1.6)x10^{-6}$ (Fig. 1). Including the Chainpur whole rock data point of [5] with our new chondrule data, changes the regressed slope only imperceptibly (from $5.11x10^{-6}$ to $5.07x10^{-6}$ ), with the same uncertainty of $±1.59x10^{-6}$ (Fig. 2). Our initial $^{53}\text{Mn}^{-55}\text{Mn}$ ratio for Chainpur is similar to the new value for Semarkona (LL3.0) chondrules, $(5.8±1.9)x10^{-6}$, obtained at the Johnson Space Center (JSC) [7]. If we regress only the chondrule data of [5] for Chainpur, we obtain $^{53}\text{Mn}^{-55}\text{Mn} = (6.9±2.0)x10^{-6}$, consistent within error with our new data. However, the latter value for the initial $^{53}\text{Mn}^{-55}\text{Mn}$ ratio is substantially lower than that reported by [5] for Chainpur chondrules (LL3.4), $^{53}\text{Mn}^{-55}\text{Mn} = (9.4±1.7)x10^{-6}$ and barely overlaps with that obtained for Bishunpur chondrules (LL3.1), $^{53}\text{Mn}^{-55}\text{Mn} = (9.5±3.1) x10^{-6}$.

Solution to the inconsistent $^{53}\text{Mn}^{-55}\text{Mn}$ ratios: We have closely reexamined the data in [5] and found that the high initial $^{53}\text{Mn}^{-55}\text{Mn}$ value of $(9.4±1.7)x10^{-6}$ for Chainpur was obtained by regression of all the chondrule data together with data from five bulk chondrites, including one whole rock Chainpur chondrite and four additional ordinary chondrites. The data for Bishunpur were treated by [5] consistently.
We note that there are no Bishunpur whole rock data reported in [5]. Applying the Ludwig Isotop 3 program to the Nyquist et al. (2001) data, we obtain $^{53}\text{Mn} / ^{55}\text{Mn} = (9.08 \pm 2.95) \times 10^{-6}$ for Chainpur and $(9.53 \pm 3.97) \times 10^{-6}$ for Bishunpur, respectively, consistent within error to the values obtained by [5] using the Williamson program. This agreement precludes the different data reduction algorithms as being the cause of the differences in the regressed slopes. Thus, the differences between the initial $^{53}\text{Mn} / ^{55}\text{Mn}$ ratios in our study and that of [5] are primarily due to the inclusion of data for four other whole rock ordinary chondrites. We suggest that the approach used here by including data only for one meteorite (Chainpur) provides a more accurate assessment of the initial abundance of $^{53}\text{Mn}$ during Chainpur chondrule formation.

Comparative chronology in the early Solar System: We use two absolute age anchors in Fig. 3, the high precision Pb-Pb ages of CAIs (filled circle, 4567.2 $\pm$ 0.6 Ma; [6]) and LEW (filled square, 4557.8 $\pm$ 0.5 Ma; [1]), respectively; the offset between the two ages is 9.4 $\pm$ 0.8 Ma. If we use instead the recently updated LEW 86010 Pb-Pb age of 4558.6 $\pm$ 0.18 Ma [8], the age difference between the two age anchors is 8.5 $\pm$ 0.63 Ma, identical within error to the previous value. The line joining the two age-anchor points shall be called the “early solar system equiline.” The $^{53}\text{Mn}$-$^{53}\text{Cr}$ systematics in CAIs are complex and not well understood [9]. The solar system’s initial abundance of $^{53}\text{Mn}$ is instead obtained from bulk carbonaceous chondrites, which give a $^{53}\text{Mn} / ^{55}\text{Mn}$ ratio of $(8.5 \pm 1.5) \times 10^{-6}$ [10]. We have also obtained a similar result for carbonaceous chondrites $(8.5 \pm 1.2) \times 10^{-6}$ [11]. Relative to this value, our Chainpur chondrules are calculated to be 2.73 Ma younger than the CAIs (Fig. 3, filled circle). Relative to the LEW/ADOR age anchor with $^{53}\text{Mn} / ^{55}\text{Mn} = (1.25 \pm 0.07) \times 10^{-6}$ [2], our Chainpur chondrules are 7.51 Ma older (filled green square). Because of the common Pb problem, there is no high precision Pb-Pb age available for the Chainpur chondrules (Y. Amelin 2007, private communication). Plotted instead on the $x$-axis in Figure 3 is the widely accepted younger $^{26}\text{Al}$-$^{26}\text{Mg}$ age for chondrules (Kita et al. 2005), 2.5 $\pm$ 1.0 Ma, relative to the CAI age anchor at 4567.2 $\pm$ 0.6 Ma [6]. Our new Chainpur data plot on the equiline within the analytical uncertainty. The new JSC Semarkona chondrule data with a $^{53}\text{Mn} / ^{55}\text{Mn}$ ratio of $(5.8 \pm 1.9) \times 10^{-6}$ give a $^{53}\text{Mn}$-$^{53}\text{Cr}$ age of 7.5 $\pm$ 2.1 Ma older than the LEW/ADOR anchor, consistent with the $^{26}\text{Al}$-$^{26}\text{Mg}$ ages of chondrules [7]. In contrast, the earlier Chainpur data [5] with an initial $^{53}\text{Mn} / ^{55}\text{Mn}$ ratio of $(9.4 \pm 1.7) \times 10^{-6}$ would correspond to an age of 10 Ma older than LEW 86010 with an uncertainty of 1–2 Ma, very similar to the time of CAI formation, but inconsistent with the $^{26}\text{Al}$-$^{26}\text{Mg}$ age of chondrules [7]. Based on the collective $^{53}\text{Mn}$-$^{53}\text{Cr}$, $^{26}\text{Al}$-$^{26}\text{Mg}$, and $^{207}\text{Pb}$-$^{206}\text{Pb}$ systematics [12-13], the Asuka 881394 eucrite also plots on the equiline; the filled circle is an $^{26}\text{Al}$-$^{26}\text{Mg}$ age relative to the CAI anchor, while the open square behind it is a $^{53}\text{Mn}$-$^{53}\text{Cr}$ age relative to the LEW/ADOR anchor. Two quenched angrites (D’Orbigny and Asuka 881371) are also plotted in Figure 3 based on literature data [14-17]. Using the latest $^{207}\text{Pb}$-$^{206}\text{Pb}$ age of 4564.65 $\pm$ 0.65 Ma [8] and $^{53}\text{Mn}$-$^{55}\text{Mn}$ initial ratio of $(3.40 \pm 0.14) \times 10^{-6}$ [18] relative to the new $^{207}\text{Pb}$-$^{206}\text{Pb}$ age anchor of 4558.6 $\pm$ 0.18 Ma [8] and respective $^{26}\text{Al}$-$^{26}\text{Mg}$=$ (1.25 \pm 0.07) \times 10^{-6}$ for LEW [2], the angrite Sahara 99555 also plots on the equiline. The very old age of 4566.18 $\pm$ 0.14 Ma reported by [19] for this angrite would plot off the equiline significantly.

Fig. 3. Consistent chronology of Chainpur chondrule plotting on the Early Solar System Equiline (ESSE). Equiline is drawn through the two age anchors commonly used in the early Solar System chronology (LEW86010 /Angra dos Reis and carbonaceous chondrite CAIs).