STATISTICAL CHRONOMETRY: ANCHORS AWAY!

S. J. Desch[1], **D. R. Dunlap**[2], **C. D. Williams**[3] and **Z. A. Torrano**[4] [1]School of Earth and Space Exploration, Arizona State University, Tempe AZ (steve.desch@asu.edu). [2]Far Away Projects, San Francisco, CA. [3]Department of Earth and Planetary Sciences, University of California, Davis, CA. [4]Earth and Planets Laboratory, Carnegie Institution for Science, Washington DC.

Introduction: Meteorites record not only *what* happened at the Solar System's birth, but *when* these events occurred. The story of planet formation relies most fundamentally on constraining the *relative* timing of events in the solar nebula after some time t=0, taken to be when Ca-rich, Al-rich inclusions (CAIs) formed or, more precisely, when the solar nebula had a particular ^{26}Al/^{27}Al ratio. Relative ages are constrained by the commonly measured Al-Mg, Mn-Cr, and Hf-W isotopic systems. Absolute ages like U-corrected Pb-Pb ages are relevant inasmuch as differences between them provide times of events after t=0. The traditional use of "anchors" to report absolute ages for meteorites introduces imprecision; the proliferation of multiple potential anchors (various achondrites or CAIs) is bewilderingly confusing and ages shift frequently; and the approach obfuscates that the real purpose is to derive relative dates of events in the solar nebula. Instead of anchors, we advocate a "statistical" approach to chronometry.

Statistical Chronometry: A single analysis yielding (^{26}Al/^{27}Al)$_0$, (^{53}Mn/^{55}Mn)$_0$, or (^{182}Hf/^{180}Hf)$_0$ in a meteorite could provide the time Δt_{26}, Δt_{53}, or Δt_{182}, at which that system achieved isotopic closure. We *define* t=0 to be when (^{26}Al/^{27}Al) = 5.23 × 10^{-5} [1], but the Solar System (^{53}Mn/^{55}Mn)$_{SS}$ and (^{182}Hf/^{180}Hf)$_{SS}$ at t=0 are unknown free parameters. To leverage Pb-Pb absolute ages, t_{Pb}, we must define the "Pb-Pb" age at t=0, t_{CAI}, as a third free parameter, to find $\Delta t_{\mathrm{Pb}} = t_{\mathrm{CAI}} - t_{\mathrm{Pb}}$. The half life, t_{53}, of ^{53}Mn (3.7 ± 0.74, 2σ) is impractically uncertain and is a fourth free parameter. We determine the optimal values of these 4 free parameters by minimizing the discrepancies between Δt_{26}, Δt_{53}, Δt_{182} and Δt_{Pb}, as determined using compiled literature values, for 12 achondrites, including: the quenched angrites D'Orbigny, SAH 99555, and NWA 1670; other angrites LEW 86010, NWA 4590, NWA 4801, Angra dos Reis, and NWA 2999; plus Asuka 881394, NWA 7325, NWA 2976, and NWA 6704. Through a statistical approach we find the **best-fit** values: $\boldsymbol{t_{\mathrm{CAI}} = 4568.61 \pm 0.26}$ **Myr**; $\boldsymbol{(^{53}\mathrm{Mn}/^{55}\mathrm{Mn})_{SS} = (8.10 \pm 0.82) \times 10^{-5}}$, $\boldsymbol{(^{182}\mathrm{Hf}/^{180}\mathrm{Hf})_{SS} = (10.44 \pm 0.27) \times 10^{-5}}$, and $\boldsymbol{t_{53} = 3.82 \pm 0.27}$ **Myr**. Using these, we show (**Figure 1**) concordancy between the systems for 10 of the 14 achondrites above, especially D'Orbigny; each of its systems is consistent with Δt = 5.05 ± 0.03 Myr (i.e., age 4563.56 ± 0.26 Myr). The only discordant examples are the plutonic angrites NWA 4590, NWA 4801 and NWA 2999, previously thought disturbed [2], and the 'carbonaceous achondrite' NWA 6704 analyzed by [3]. Our 4-parameter model brings 24 ages of 8 achondrites into concordance.

Implications: Our approach makes **no** reference to CAIs except the ^{26}Al/^{27}Al ratio, yet fixes t_{CAI}, (^{53}Mn/^{55}Mn)$_{SS}$, and (^{182}Hf/^{180}Hf)$_{SS}$ more precisely than do direct measurements of CAIs. Our results compare favorably with (^{53}Mn/^{55}Mn)$_{SS}$ = (7 ± 1) × 10^{-5} [6], and (^{182}Hf/^{180}Hf)$_{SS}$ = (10.18 ± 0.43) × 10^{-5} [7], and with t_{CAI} = 4568.2 ± 0.3 Myr [4] but not at all with 4567.3 ± 0.3 Myr [5]. We leverage multiple measurements simultaneously, minimizing the effects of analytical uncertainties; uncertainty is dominated by the half-lives of ^{26}Al (0.717 ± 0.34 Myr, 2σ [8]), and ^{182}Hf (8.9 ± 0.18 Myr, 2σ). Typical formation time uncertainties are < 0.1 Myr. Our approach naturally accommodates new data, which would improve the precision without shifting these best-fit values much. Our approach identifies which systems, chondrites, or laboratories are most discordant. The overall concordancy argues strongly for homogeneity of ^{26}Al, ^{53}Mn, and ^{182}Hf in the solar nebula.

References: [1] Jacobsen, B. et al. 2008. *EPSL* 272:353-364. [2] McKibbin, S. J. et al. 2015. *GCA* 157:13-27. [3] Sanborn, M. et al. 2019. *GCA* 245:577-596. [4] Bouvier, A. and Wadhwa, M. 2010. *Nat. Geo.* 3:637-641. [5] Connelly, J. N. et al. 2012. *Science* 338: 651-655. [6] Tissot, F. L. H. et al. 2017. *GCA* 213:593-617. [7] Kruijer, T. S. et al. 2014. *EPSL* 403:317-327.[8] Auer, M. et al. 2009. *EPSL* 287:453-462.

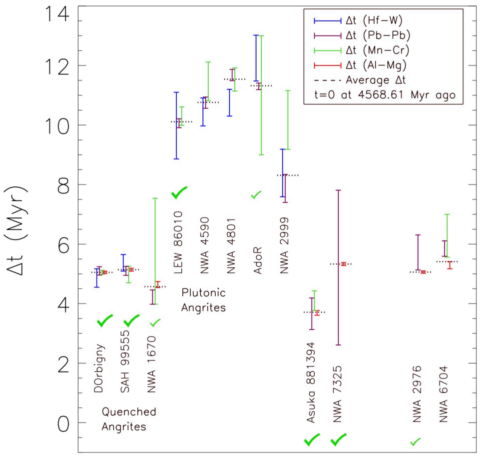

Figure 1: Thirty-six times of formation after t=0 (when ^{26}Al/^{27}Al=5.23×10^{-5}) for 12 achondrites, using literature measurements of the Hf-W, Mn-Cr, Al-Mg and Pb-Pb systems, and our best-fit parameters for absolute age of CAIs, initial solar nebula (^{53}Mn/^{55}Mn) and (^{182}Hf/^{180}Hf), and ^{53}Mn half life. The excellent concordancy for the 8 least disturbed achondrites demonstrates the advantages of statistical chronometry over anchors, especially CAIs.