A COMBINED AL-MG/PB-PB AGE OF THE SOLAR SYSTEM. S. J. Desch[1], D. R. Dunlap[2], C. D. Williams[3], P. Mane[4,5,] and E. T. Dunham[6], [1]School of Earth and Space Exploration, Arizona State University, Tempe AZ (steve.desch@asu.edu); [2]Oak Ridge National Laboratory, Oak Ridge, TN; [3]Earth and Planetary Sciences Dept., U. California, Davis; [4]Lunar and Planetary Institute, Houston, TX; [5]Astromaterials Research Exploration Sciences, NASA Johnson Space Center, Houston, TX; [6]Dept. Earth, Planetary & Space Sciences, U. California, Los Angeles.

Introduction: Astrophysical models of planet formation and protoplanetary disk evolution demand precise and accurate timing of the sequence of events in the solar nebula, relative to a time t=0, usually taken to be during the short epoch of CAI (Ca-rich, Al-rich inclusion) formation. Most CAIs formed with live ^{26}Al (mean-life τ_{26} = 1.034 Myr [1]), with an abundance $^{26}\mathrm{Al}/^{27}\mathrm{Al} \approx (^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\mathrm{SS}} = 5.23 \times 10^{-5}$ [2]. We adopt this as the widespread level of ^{26}Al in the solar nebula at t=0. Assuming spatial homogeneity of ^{26}Al, an inclusion that had less ^{26}Al, $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, formed a time $\Delta t_{26} = \tau_{26} \ln [(^{26}\mathrm{Al}/^{27}\mathrm{Al})_{\mathrm{SS}} / (^{26}\mathrm{Al}/^{27}\mathrm{Al})_0]$ after t=0. These ages are typical precise to within ±0.1 Myr.

Igneous bulk meteorites and inclusions can be relatively dated by the Al-Mg chronometer, but only if Δt_{26} < 6 Myr. The Pb-Pb system is useful as a longer *relative* chronometer. It yields absolute ages t_{Pb} using $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$, and $^{238}\mathrm{U}/^{235}\mathrm{U}$ ratios measured in different portions of a sample, assuming certain half-lives [4]. These absolute ages are uncertain to within ±9 Myr due to uncertainties in the ^{235}U half-life [3], but times of formation $\Delta t_{\mathrm{Pb}} = t_{\mathrm{CAI}} - t_{\mathrm{Pb}}$ relative to t=0, are more precise (±0.5 Myr), **if** t_{CAI} can be found. Here, t_{CAI} means the Pb-Pb age that would be measured in CAIs using the half-lives the community typically uses, if they achieved isotopic closure at t=0.

Unfortunately, direct Pb-Pb dating of CAIs has not definitively determined t_{CAI}. Based on four CAIs with canonical $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, [5,6] found t_{Pb} = 4567.30 ± 0.16 Myr. No other CAI ages with measured $^{238}\mathrm{U}/^{235}\mathrm{U}$ have been reported in the refereed literature, but there are hints of other CAIs with ages t_{Pb} = 4568.0 ± 0.2 Myr [7] and t_{Pb} = 4568.3 ± 0.2 Myr [8]. It is unclear whether *any* of these igneous type B CAIs isotopically closed at t=0 or represents t_{CAI}.

Instead of measurements, we advocate finding t_{CAI} by minimizing the discrepancies between the Al-Mg and Pb-Pb chronometers. Assuming $\Delta t_{26} = \Delta t_{\mathrm{Pb}}$, we find the implied $t'_{\mathrm{CAI}} = t_{\mathrm{Pb}} + \Delta t_{26}$, then define t^*_{CAI} as the weighted mean of the t'_{CAI}. t^*_{CAI} is the best guess for the Pb-Pb age of t=0; the assumption of homogeneity is justified if the t'_{CAI} cluster within errors around t^*_{CAI}. This statistical approach is similar to, but improves on, that of [9]. We find $\boldsymbol{t^*_{\mathrm{CAI}}}$ **= 4568.73 ± 0.16 Myr.** Below we discuss our methodology and the implications of this age for CAIs, 1.4 Myr older than the reported and typically used age 4567.30±0.16 Myr.

Methods: We base our estimate of t^*_{CAI} on five achondrites for which published $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ and Pb-Pb ages exist: the quenched angrites D'Orbigny, Sahara 99555 (SAH 99555), and Northwest Africa (NWA) 1670; the pseudo-eucrite Asuka 881394; and the inner disk achondrite. All are "NC" (non-carbonaceous) achondrites that likely cooled quickly enough that the Al-Mg and Pb-Pb systems achieved isotopic closure simultaneously. We also considered the "CC" (carbonaceous chondrite-like) achondrites NWA 2796 and NWA 6704, but do not include them in our fit. Al-Mg and Pb-Pb seem not to have closed simultaneously, possibly because formation in the outer disk from volatile-rich composition led to slower cooling. Of the 8 chondrules from NWA 5697 measured by [20,21], we also consider the 4 for which $^{238}\mathrm{U}/^{235}\mathrm{U}$ was measured: 2-C1, 5-C2, 3-C5, 11-C1. Depending on their post-formation thermal histories, the Al-Mg and Pb-Pb systems in chondrules may or may not have closed simultaneously.

Table 1: $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, Pb-Pb ages of selected samples

Sample	$(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ / 10^{-6}	Ref	Pb-Pb	Ref
D'Orbigny	3.98±0.15	10	4563.43±0.19♮	10-12
SAH 99555	3.64±0.18	10	4563.88±0.27	12
NWA1670	5.92±0.59	10	4564.39±0.24*	10
Asuka 881394	13.1±0.56	13-15	4564.98±0.17	15
NWA 7325	3.03±0.14	16	4563.4±2.6	16
NWA 2796	3.94±0.16	17	4562.89±0.59	17
NWA 6704	3.03±0.14	18	4562.76±0.26	19
2-C1	7.56±1.53	20	4567.57±0.56*	21
5-C2	7.04±1.51	20	4567.54±0.52*	21
3-C5	8.85±1.83	20	4566.20±0.63*	21
11-C1	5.55±1.84	20	4565.84±0.72*	21

*regression based on one subset of data points
♮weighted mean of two datasets

Pb-Pb ages are proportional to the intercept of the line formed by linear regression of $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ vs. $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ data from various washes, leachates and residues of acid dissolution of a sample. Because contamination by terrestrial or primordial Pb is pervasive, some fractions must be excluded from regressions to ensure a fit with acceptable mean squares weighted deviation (MSWD). Usually points are excluded based on low [Pb], or low $^{206}Pb/^{204}Pb$ ratio (low radiogenic component), with single outliers identified [11,12,15,16,17]. In the starred examples (Table 1) and the case of 3 CAI Pb-Pb ages [5], up to half the points were excluded *solely* because did not fit a pre-determined line. This approach is vulnerable to confirmation bias and produces fits with low MSWD and too-low Pb-Pb age uncertainty. Regressing the same data points as [10], we reproduce the Pb-Pb age of NWA 1670 of 4564.39±0.24 Myr. But selecting other combinations of data points, other, equally valid, isochrons yield ages from 4563.77±0.21 Myr to 4564.64±0.23 Myr. Similar arguments apply to the Pb-Pb isochrons built by [21] for chondrules 2-C1 (we find 4567.33±0.44 to 4567.85±0.46 Myr), 5-C2 (4566.84±0.53 to 4567.70±0.44 Myr), 3-C5 (4565.84±0.54 to 4567.04±0.54) and 11-C1 (4565.36±0.51 to 4565.74±0.45 Myr). Our adopted ages for these and NWA 1670 are listed in Table 2.

Table 2. t_{CAI} estimated from various components, using our regressions for the chondrules & NWA 1670.

Sample	**Δt_{26} (Myr)**	**t_{Pb} (Myr)**	**t'_{CAI} (Myr)**
D'Orbigny	5.05±0.04	4563.43±0.19	4568.48±0.19
SAH 99555	5.14±0.05	4563.88±0.27	4569.02±0.27
NWA1670	4.64±0.10	4564.21±0.63	4568.85±0.67
Asuka 881394	3.81±0.04	4564.98±0.17	4568.79±0.17
NWA 7325	5.33±0.05	4563.4±2.6	4568.7±2.6
NWA 2796	5.06±0.04	4562.89±0.59	4567.95±0.59
NWA 6704	5.29±0.13	4562.76±0.26	4568.05±0.29
2-C1	2.00±0.21	4567.59±0.70	4569.59±0.72
5-C2	2.07±0.22	4567.23±0.91	4569.30±0.93
3-C5	1.84±0.21	4566.44±1.12	4568.28±1.14
11-C1	2.32±0.34	4565.52±0.66	4567.84±0.73
achondrite			4568.72±0.16
chondrules			4568.76±0.58
combined			**4568.73±0.16**

A weighted average of the five NC achondrites (or just D'Orbigny, SAH 99555 and Asuka 881394) yields t^*_{CAI} = 4568.72 ± 0.16 Myr. All are consistent with this value to within 1.8σ, and MSWD=1.5. Including the 4 U-corrected chondrules, $\boldsymbol{t^*_{CAI}}$ **= 4568.73 ± 0.16 Myr** with MSWD=1.66, which is statistically significant. All chondrules and NC achondrites are consistent with this to within 1.8σ, **(Figure 1).**

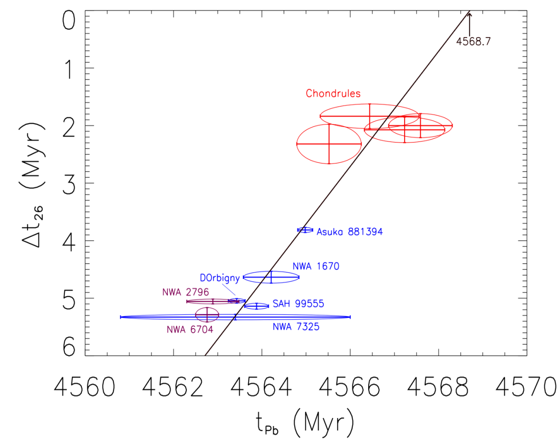

Figure 1. Al-Mg formation times after *t*=0 vs. Pb-Pb ages. The five NC achondrites and four chondrules are consistent with a Pb-Pb age of *t*=0 of 4568.7 Myr.

Discussion: The data from achondrites and chondrules are consistent with a single Pb-Pb age at *t*=0, justifying the assumption of ^{26}Al homogeneity. The age, 4568.7 Myr, is ≈1.4 Myr older than the commonly accepted Pb-Pb age of CAIs that formed with canonical $^{26}Al/^{27}Al$ at *t*=0 [3]. Others have interpreted the discrepancy to signify ^{26}Al heterogeneity in the CAI-forming region [5, 21]. We suggest instead that CAIs were exposed to transient heating events that reset the Pb-Pb system without disturbing the Al-Mg system. Notably, chondrules typically experienced transient heating at these times in the nebula [22]. If so, direct measurements of CAIs will not yield as reliable a Pb-Pb age of *t*=0 as statistical approaches like this and that of [9].

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