MOLYBDENUM ISOTOPIC EVIDENCE FOR A DISTAL FORMATION OF REFRACTORY INCLUSIONS. G.A. Brennecka[1*], C. Burkhardt[1], F. Nimmo[2], T.S. Kruijer[3], T. Kleine[1], [1]Institut für Planetologie, University of Münster. [2]Dept. Earth & Planetary Sciences, University of California Santa Cruz, CA, [3]Lawrence Livermore National Laboratory, Livermore, CA. (*brennecka@gmail.com)

Introduction: Calcium-aluminum-rich inclusions (CAIs) are the oldest dated materials in the Solar System. Thus, identifying the astrophysical setting for the most likely region of CAI formation is essential for understanding the earliest period of Solar System development. Based on the specialized mineralogy, unique chemical and isotopic compositions (in particular O), and the inferred initial abundances of certain short-lived radionuclides, there is a widely held view that CAI formation occurred near the young Sun (<0.1 AU), followed by substantial outward transport to the accretion region of their host meteorite or cometary bodies [1]. However, to this point, no data have been presented that definitively either rule out or require CAI formation in specific regions of the solar nebula.

Recent work has shown that meteoritic material of the Solar System can be seen to be divided into two distinct categories, termed “non-carbonaceous” (NC) and “carbonaceous” (CC) meteorites [2], which likely were separated by the early formation of Jupiter [3, 4]. This emerging gas giant effectively separated the Solar System into inner and outer regions, revealed by Mo isotopic signatures. The members of each group vary by the amount of *s*-process Mo, and the offset between the two groups is due to a relative excess of *r*-process material in the CC reservoir [3]. Thus, Mo isotopes are powerful tracers for distinguishing between materials that formed in the inner (NC) and outer (CC) Solar System.

In this work, we investigate the Mo isotopic systematics of a variety of CAIs in an attempt to better understand the astrophysical setting and formation region of CAIs, and how CAIs are genetically linked to later formed Solar System objects.

Samples & Methods: Six coarse-grained and four fine-grained CAIs from the CV3 chondrites Allende (N=8), NWA 6870, and NWA 6717 originally investigated for W isotopes [5] were examined for their Mo isotopic composition. Mo was isolated using ion exchange chemistry outlined in previously established methods [6] and isotopic compositions of Mo were measured on a Neptune*Plus* MC-ICPMS in the Institut für Planetologie in Münster.

Results: The Mo isotopic compositions of all CAIs are distinct from the terrestrial standard. The Mo isotopic signatures of the coarse-grained CAIs are virtually indistinguishable from one another and are analogous to previously reported data of coarse-grained CAIs, having an excess in *r*-process Mo relative to Earth [6-8]. On the other hand, the fine-grained CAIs analyzed here have variable *s*-process character and show not only large variations from their coarse-grained cousins, but also large variations from one another. Together with the previously reported non-coarse grained CAI A-ZH-5 [6], the combined data span a range of ~40 ε^{94}Mo and reveal variable depletions/enrichments in *s*-process Mo relative to the terrestrial composition (Fig.1).

Discussion: The implications of the results for the formation of CAIs are perhaps best understood in the context of previously obtained Mo data from other Solar System materials. The distinction between the NC and CC meteorite groups [3] is most easily seen when plotting samples on an ε^{95}Mo vs. ε^{94}Mo diagram, where the groups essentially plot along two parallel lines (Fig 1, zoom). Based principally on the members of each group (*i.e.*, iron meteorites, ordinary & enstatite chondrites in the NC group; carbonaceous chondrites and iron meteorites in the CC group), it has been suggested that the NC and CC formation regions represent the inner Solar System and outer Solar System, respectively, kept separate by the early formation of Jupiter [3, 4].

Given these groupings, it is perhaps unsurprising that chemical separates of the CC-group Orgueil CI [9] and Murchison CM2 chondrites [10] correlate along an *s*-process mixing line (Fig. 1) that is indistinguishable from the one established by bulk CC meteorites. Such a linear correlation includes Allende chondrule and matrix separates [3], suggesting a similar isotopic heritage and formation region for all of these samples, and one that was possibly beyond the orbit of Jupiter [4].

Intriguingly, the fine-grained CAIs also plot along an *s*-process mixing line with a virtually identical slope and intercept to samples belonging to the CC group reported by previous studies (Fig. 1). These isotopic similarities strongly imply that the Mo hosted in all of these samples share a common ancestry—one that is notably different from both that of coarse-grained CAIs and the NC group of meteorites. Thus, the strong genetic connection between fine-grained CAIs and carbonaceous meteorites strongly suggests that fine-grained CAIs formed beyond the orbit of Jupiter.

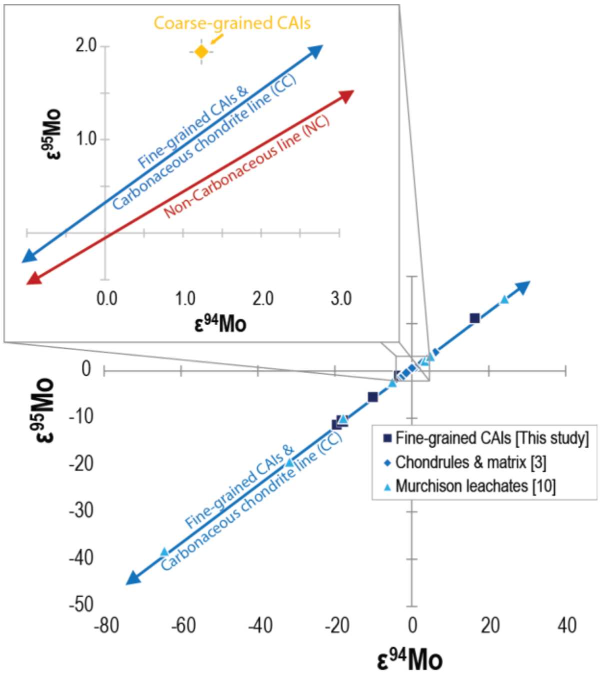

Fig. 1. Isotopic relationship between fine-grained CAIs and other materials of the CC meteorite grouping. The zoom panel shows the separation of the NC and CC meteorites and the average (and homogenous) value of igneous CAIs.

The Mo isotope signatures of coarse-grained CAIs are less distinctive in terms of their formation region, because these CAIs neither plot on the CC- nor on the NC-line. It is noteworthy, however, that the Mo *r*-process excess signature in coarse-grained CAIs (shown in Fig. 1) may represent the composition of the material whose addition is likely responsible for the apparent excess of ^{95}Mo in the CC region. Thus, one possibility is that coarse-grained CAIs formed from late-infalling material that was isotopically distinct from material in the inner Solar System. Admixture of this material then gave rise to the distinct isotopic composition of the CC reservoir, while this material was not added to the NC reservoir due to the Jupiter barrier. In this context, the fine-grained CAIs, which plot on the CC-line, would have formed after admixture and homogenization of the late-infalling material, because otherwise they would not have a persistent *r*-process excess compared to the NC reservoir (*i.e.*, they would not plot on an *s*-process mixing line parallel to the NC line). Thus, the Mo isotopic data are consistent with formation of both coarse- and fine-grained CAIs in the outer Solar System, and their distinct isotopic signatures might either represent different formation locations within the CC region, or distinct formation times.

Implications: The widely held view of CAI formation near the young Sun (<0.1 AU) is based primarily on constraints from temperature regimes and environmental conditions; however, if such temperature regimes and environmental conditions were present elsewhere in the Solar System, formation of CAIs would be possible in any area with said conditions.

Perhaps one of the most stringent requirements on the astrophysical setting of CAI formation—and a primary reason for hypothesizing they formed near the Sun—is the high temperature mandated by the unique mineralogy of CAIs. As is evident from the ubiquitous presence of chondrules in carbonaceous and non-carbonaceous chondrites, temperatures high enough for chondrule formation were possible, if not common, in the outer Solar System. Thus, it is conceivable that temperatures high enough for CAI formation were also present. For instance, if Jupiter's ~10 Earth-mass core formed rapidly via pebble accretion [11], high effective temperatures would result: roughly 2600 K for an 0.1 Myr accretion timescale, higher than the temperatures mandated by CAI mineralogy. Moreover, as Jupiter formed, it went through a period of very high luminosity, up to ~1% of the solar luminosity for a few hundred ka [12], which may have provided the conditions necessary for CAI formation. Although in these scenarios it is unclear how efficient the process was, and why CAIs would have been preserved and not accreted to Jupiter, the small grain size of the CAI's relative to larger pebbles may have played a role. Undoubtedly, more work is required to assess the dynamics of high-temperature processes surrounding a rapidly forming Jupiter.

Even if the thermal conditions of CAI formation are met by heat produced from planetary formation, additional constraints regarding relocating the CAI-formation region must be satisfied. Any model of CAI formation must address the unique isotopic signatures of CAIs, particularly in O isotopes. In this case, if CAIs did form in the outer Solar System as our data suggest, the stark isotopic differences between CAIs and later formed objects in a major element like O would most easily be explained by mixing between gas and dust that were isotopically distinct, as suggested by [12].

References: [1] Wood (2004) *GCA*, *68*, 4007. [2] Warren (2011) *EPSL*, *311*, 93. [3] Budde et al. (2016) *EPSL*, *454*, 293. [4] Kruijer et al. (2017) *PNAS*, *114*, 6712. [5] Kruijer et al. (2014) *EPSL*, *403*, 317. [6] Burkhardt et al. (2011) *EPSL*, *312*, 390. [7] Yin et al. (2002) *Nature*, *415*, 881. [8] Brennecka et al. (2013) *PNAS*, *110*, 17241. [9] Dauphas & Reisberg (2002) *ApJ*, *565*, 640. [10] Burkhardt et al. (2012) *ESPL*, *357-358*, 298. [11] Levison et al. (2015) *Nature 524*, 322. [12] Marley et al. (2007) *ApJ*, *655*, 541. [13] Krot et al (2010) *ApJ*, *713*, 1159.