**ABSOLUTE CHRONOLOGY OF THE FIRST SOLIDS IN THE SOLAR SYSTEM.** A. Bouvier[1], G. A. Brennecka[1] and M. Wadhwa[1], [1]Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, 85287 USA (email: audrey.bouvier@asu.edu).

**Introduction:** The chronology of early Solar System processes and the determination of the initial abundance of short-lived radionuclides (e.g., $^{26}$Al, $^{60}$Fe, $^{146}$Sm) are best contrained by comparing the isotopic records of absolute (live) and relative (extinct) radiogenic chronometers applied to meteoritic objects (e.g., see abstracts for this workshop by Amelin et al., Nyquist and Bogard). The precision and accuracy of the dates obtained using many of the radiochronometers (e.g., U-Pb, Sm-Nd, Rb-Sr, Lu-Hf) are hindered by factors such as uncertainties in their half-lives and the possibility of fractionation (for example, during chemical processing in the laboratory) of the radiogenic parent/daughter isotope ratios. The Pb-Pb chronometer is a unique high-resolution absolute clock for deciphering the chronology of early Solar System processes. This chronometer is only dependent on a precise determination of the radiogenic Pb isotopic composition ($^{207}$Pb*/$^{206}$Pb*) since the closure of the two U-Pb systems (i.e., the $^{238}$U and $^{235}$U decay chains) and knowledge of the $^{238}$U/$^{235}$U ratio. In principle, if these parameters are well known, this chronometer is able to resolve absolute age differences of ≤100,000 years for early Solar System objects (e.g., [1, 2]).

The Pb-Pb ages determined for calcium-aluminum rich inlcusions (CAIs) from the Allende, Efremovka, and NWA 2364 CV chondrites vary between 4566.7 ± 0.2 and 4568.2 ± 0.2 Ma [1, 3] if assuming a $^{238}$U/$^{235}$U = 137.84 [4, 5]. However, this apparent ~1.5 Ma range of absolute ages is not consistent with a short formation interval of ≤300 ka for CAIs deduced from their $^{26}$Al-$^{26}$Mg systematics (e.g., [6-8]). This range of CAIs ages is more likely explained by secondary disturbance of Pb isotope systematics and/or variation in the U isotopic composition in these CAIs. Indeed, U isotopic variations have been found, first in terrestrial rocks [9, 10], and shortly thereafter in meteoritic objects [11]. These findings necessitate the precise measurement of the U isotopic composition of any planetary object dated with the Pb-Pb method. In particular, this is crucial for meteoritic materials that are to be used as age anchors for short-live radiochronometers.

**U isotopic compositions of CAIs and Pb-Pb age implications:** In the U isotopic study of CAIs of the Allende CV3 chondrite by [11], it was demonstrated that the measured $^{238}$U/$^{235}$U ratio was correlated with the corresponding Th/U or Nd/U of the inclusions (blue and red symbols in Fig. 1). These results were interpreted as consequence of the presence of live $^{247}$Cm that decayed to $^{235}$U ($T_{1/2}$~15.6 Ma) in the early Solar System. The SJ-101 CAI of Allende, described as a group II inclusion [12], is the only one that has a $^{238}$U/$^{235}$U lower than that of the terrestrial standard value of 137.84 (Fig. 1). This CAI suggests that other processes such as isotopic fractionation or nucleosynthetic anomalies may also be responsible for U isotopic variations in meteoritic materials. Taken together, the $^{238}$U/$^{235}$U ratios measured in Allende CAIs range from +0.3‰ to -3.5‰ (relative to the identical U standards SRM950 or CRM145) and correspond to corrections on Pb-Pb dates of +0.4 to -5 Ma relative to the previously assumed constant $^{238}$U/$^{235}$U (=137.88) [11, 13].

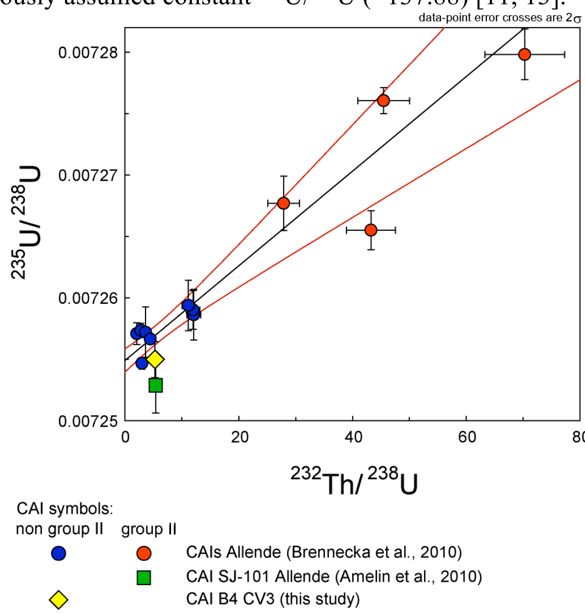


Fig. 1: $^{232}$Th/$^{238}$U vs. $^{235}$U/$^{238}$U in CAIs ([11, 13] and this study). The solid black and red lines represent the best fit and error envelope, respectively, for the Allende CAI data from [11], reported relative to the recently determined value of the $^{238}$U/$^{235}$U ratio (=137.84) for the SRM950a standard [4,5].

**New Results:** We present here the elemental, U and Pb isotopic composition of a coarse-grained CAI (hereafter named B4) from a newly recovered CV3 chondrite (provided by M. Farmer). The analytical techniques used are described in [3, 11]. The Al-Mg investigation of this CAI is in progess.

The bulk elemental composition of the CAI B4 indicates that this object has a flat REE pattern $(La/Lu)_N$ ~0.9 and a slight positive Eu anomaly $(Eu/Eu^*)_N$ ~1.2 anomaly, therefore it is not a group II CAI. This inclusion has a $^{232}Th/^{238}U$ = 5.2 and $^{144}Nd/^{238}U$ = 13.7 (±5%). The $^{238}U/^{235}U$ ratio measured in the same bulk solution is 137.837 ± 0.028 (relative to SRM950a = 137.84; error based on 2SD of repeat runs of the standard measured at a similar concentration as the sample in the same analytical session). The composition of the CAI B4 falls within the error envelope of the trend defined by Allende CAIs in the plot of Th/U (and Nd/U) vs. $^{235}U/^{238}U$ [11] (Fig. 1). The Pb-Pb internal isochron age obtained for leached fractions of melilite and fassaite separates of the CAI B4 is 4567.94 ± 0.31 Ma using its measured U isotopic composition (Fig. 2).

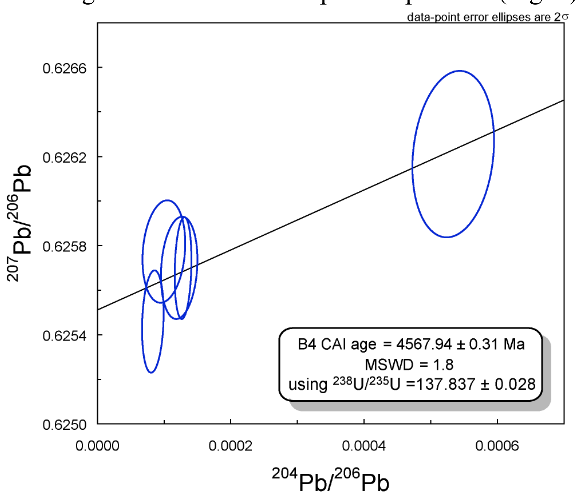


Fig. 2: The Pb isotope systematics of two melilite and one fassaite separates (residues and last leachate with blank corrected $^{206}Pb/^{204}Pb$ >1,800) from the CAI B4. The Pb-Pb age of 4567.94 ± 0.31 Ma is calculated using its measured U isotopic composition of $^{238}U/^{235}U$ = 137.837 ± 0.028.

**Discussion:** The Pb-Pb age of the Allende group II CAI SJ-101 (using its measured U isotope composition) is 4567.18 ± 0.50 Ma [13]. This age is resolvably younger than the age reported here of the non group II CAI B4 (with its measured U isotope composition that is identical within errors to the value for the terrestrial standard of 137.84). Therefore, even after accounting for possible U isotopic variations, the range of Pb-Pb ages of CAIs still extends over ~0.7 Ma. Possible explanations for this may include Pb isotopic fractionation following CAI formation, either during late parent body processes, or possibly even during leaching in the laboratory [13].

The use of SJ-101 or B4 as age anchors for short-lived radioactivities has different implications for the degree of homogeneity of $^{26}Al$ in the solar nebula. The Pb-Pb age of SJ-101 is consistent with Hf-W systematics in CAIs and angrites [14] and suggests a heterogeneous distribution of $^{26}Al$ (as also recently suggested by [15]). In contrast, the Pb-Pb age of the CAI B4 is consistent with Al-Mg and Mn-Cr systematics (assuming a canonical $^{26}Al/^{27}Al$ and an initial Solar System $^{53}Mn/^{55}Mn$ from [16]) of angrites and the ungrouped NWA 2976 achondrite [17], and implies a homogeneous distribution of $^{26}Al$. Homogeneity of $^{26}Al$ is also suggested by precise in-situ Al-Mg measurements of chondrules that are consistent with an isotopic evolution from a canonical CAI reservoir [18].

**Future Directions for high-precision Pb-Pb chronometry:** The initial Pb isotopic composition of the Solar System is defined by the troilite composition from IAB iron meteorites [19] which is commonly used for Pb-Pb model age calculations assuming a single-stage isotopic evolution. However, troilites crystallized from a differentiated reservoir on the iron meteorite parent body about ~2-5 Ma after CAIs [20] and no correction has been made for the U isotopic composition of the troilites and respective parent bodies [2, 19]. Another outstanding problem is an apparent discrepancy of ~1 Ma on CAI model ages from Hf-W and Al-Mg and Mn-Cr systematics when anchored to the D'Orbigny angrite [3]. The Allende parent body has seen significant secondary processing, the effects of which on the different isotope systems in CAIs are not well known. Consequently, there is a need to investigate a range of radiogenic isotope systematics in different CAI types extracted from a variety of primitive chondrites. Future work on such inclusions, including UN and FUN inclusions, must also include detailed petrographic and chemical documentation to better assess the processes responsible for the isotopic characteristics in these inclusions.

**References:** [1] Amelin Y. et al. 2009. *GCA, 73*, 5212-5223. [2] Blichert-Toft J. et al. 2010. *Earth Planet. Sci. Lett., 300*, 152-163. [3] Bouvier A. and Wadhwa M. 2010. *Nature Geosci., 3*, 637-641. [4] Condon D. J. et al. 2010. *GCA, 74*, 7127-7143. [5] Richter S. et al. 2010. *Int. J. Mass Spectrom., 295*, 94-97. [6] Jacobsen B. et al. 2008. *Earth Planet. Sci. Lett., 272*, 353-364. [7] MacPherson G. J. et al. 2010. *Ap. J. Lett., 711*, L117. [8] Simon J. I. and Young E. D. 2011. *Earth Planet. Sci. Lett., 304*, 468-482. [9] Stirling C. H. et al. 2007. *Earth Planet. Sci. Lett., 264*, 208-225. [10] Weyer S. et al. 2008. *GCA, 72*, 345-359. [11] Brennecka G. et al. 2010. *Science, 327*, 449-451. [12] Jacobsen S. B. et al. 2007. *Workshop on Chronology of Meteorites,* A#4070. [13] Amelin Y. et al. 2010. *Earth Planet. Sci. Lett., 300*, 343-350. [14] Kleine T. 2011. *Min. Mag., 75*, A#1191. [15] Larsen K. et al. (2011) *Ap. J. Lett., 735*, L37. [16] Nyquist L. et al. (2009) *GCA, 73*, 5115-5136. [17] Bouvier A. et al. 2011. *GCA, 75*, 5310-5323. [18] Villeneuve J. et al. 2009. *Science, 325*, 985-988. [19] Blichert-Toft et al. 2010. *Earth Planet. Sci. Lett., 300*, 152-163. [20] Schulz T. et al. 2009. *Earth Planet. Sci. Lett., 280*, 185-193.