

**DIFFERENCE IN Pb ISOTOPIC AGES OF CHONDRULES AND CA, AL-RICH INCLUSIONS FROM THE CV CARBONACEOUS CHONDRITE ALLENDE.** J.N. Connelly<sup>1,2\*</sup>, Y. Amelin<sup>3</sup>, A.N. Krot<sup>4</sup>, and M. Bizzarro<sup>2,5</sup>. <sup>1</sup>Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA, \*connelly@mail.utexas.edu. <sup>2</sup>Geological Institute, Copenhagen University, Copenhagen, Denmark, <sup>3</sup>Australian National University, Canberra, Australia, <sup>4</sup>University of Hawai'i at Manoa, Honolulu, Hawaii, USA. <sup>5</sup>Geological Museum, Copenhagen, Denmark.

**Introduction.** Chondrules and Ca,Al-rich inclusions (CAIs) are the major components of chondritic meteorites (chondrites) and are among the earliest solids formed in the solar nebula – the disk of dust and gas that surrounded the proto-Sun [1]. Compositions and textures of CAIs and chondrules indicate that they formed by high temperature processes that included condensation, evaporation, and, for chondrules and some CAIs, subsequent melting of the early condensates during multiple brief heating episodes, possibly induced by shock waves [e.g., 2]. The age relationship between CAIs and chondrules can provide important constraints on their origin and the chronology of the solar nebula [3]. This age relationship can be potentially established using the short-lived radionuclide <sup>26</sup>Al [ $t_{1/2} = 0.73$  million years (Ma)], which was present in the nebular regions where CAIs and chondrules formed [4-12]. Based on the observations that most CAIs in primitive (unmetamorphosed) chondrites appear to have formed with an initial <sup>26</sup>Al/<sup>27</sup>Al ratio [ $(^{26}\text{Al}/^{27}\text{Al})_0$ ] of  $\sim 6 \times 10^{-5}$ , whereas most chondrules apparently formed with a  $(^{26}\text{Al}/^{27}\text{Al})_i \leq 1.2 \times 10^{-5}$ , it is commonly inferred that CAIs formed at least 1.5 Ma before the majority of chondrules [4-13].

This chronological interpretation is, however, model dependent: it is based on the assumption that <sup>26</sup>Al was homogenized in the solar nebula over a time scale that was short compared to its half-life [4]. Homogeneous distribution is readily achieved if <sup>26</sup>Al was produced by stellar nucleosynthesis in a supernova, an asymptotic giant branch star, or a Wolf-Rayet star, and was injected into the solar nebula [14]. The recent discovery of the short-lived radionuclide <sup>60</sup>Fe ( $t_{1/2} = 1.5$  Ma) in chondrites [15-17] at the level that can only be produced in massive (>10 M<sub>⊙</sub>) stars, indicates that our Solar System must have formed near one or several massive stars, and most massive stars are thought to form in dense clusters [18]. However, the lack of <sup>60</sup>Fe in meteorites from several differentiated asteroids, which accreted early (~0.5-0.7 Ma after formation of CAIs with the canonical  $(^{26}\text{Al}/^{27}\text{Al})_0$ ) with high abundances of <sup>26</sup>Al, suggests that <sup>60</sup>Fe and <sup>26</sup>Al were decoupled; i.e., they either formed by different mechanisms or were injected into the Solar System at different stages of its evolution [19].

Based on the high precision whole-rock magnesium isotopic compositions of terrestrial samples, Martian meteorites and chondrites, it has been inferred that <sup>26</sup>Al was uniformly distributed at least in the inner Solar System [20, 21]. Although these observations support the chronological interpretation of <sup>26</sup>Al-<sup>26</sup>Mg systematics, they do not prove it.

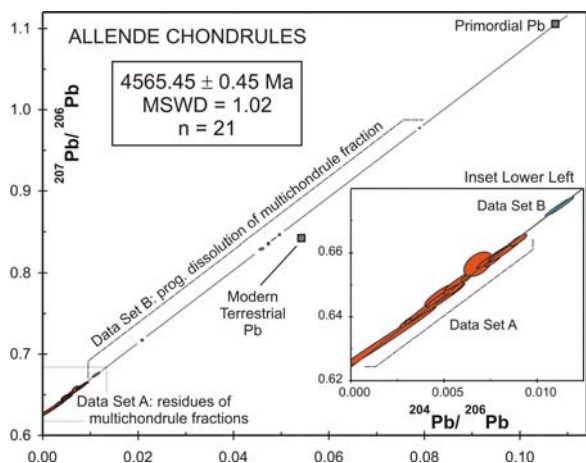
According to the alternative X-wind model, CAIs and chondrules formed contemporaneously in isotopically distinct and spatially separated nebular reservoirs and the observed differences in the  $(^{26}\text{Al}/^{27}\text{Al})_0$  reflects local formation of <sup>26</sup>Al by energetic particle irradiation near the proto-Sun [22, 23]. The abundances of <sup>26</sup>Al in this model have no direct chronological meaning. The X-wind model received significant attention after discovery of several short-lived radionuclides – <sup>10</sup>Be [24], <sup>7</sup>Be [25], and <sup>36</sup>Cl [26, 27] – that can be produced only by nuclear spallation reactions. In addition, theoretical calculations [e.g., 28] are able to reproduce within a factor of a few the initial abundances of most short-lived radionuclides reported in meteorites (<sup>10</sup>Be, <sup>26</sup>Al, <sup>36</sup>Cl, <sup>41</sup>Ca, <sup>53</sup>Mn; <sup>60</sup>Fe is the only exception).

In contrast to the short-lived, relative isotope chronologies (e.g., <sup>26</sup>Al-<sup>26</sup>Mg, <sup>53</sup>Mn-<sup>53</sup>Cr), the long-lived Pb-Pb isotope chronology of CAIs and chondrules provides absolute ages, which can potentially test whether the age differences between these objects inferred from the extinct chronometers are correct. Amelin et al. [29] first reported a resolvable Pb isotopic age difference of CAIs from the CV chondrites Allende and Efremovka ( $4567.2 \pm 0.7$  Ma, revised to  $4567.11 \pm 0.16$  [30]) and chondrules from the CR chondrite Acfer 059 ( $4564.7 \pm 0.6$  Ma). This result, however, does not preclude contemporaneous formation of chondrules and CAIs as suggested by X-wind model [22, 23, 28], since CAIs and chondrules analyzed by Amelin et al. [29] are from different chondrite groups. Here we report a resolvable <sup>207</sup>Pb-<sup>206</sup>Pb age difference between CAIs and chondrules from the CV carbonaceous chondrite Allende. Previous attempts to resolve a Pb isotopic age difference between CAIs and chondrules from CV chondrites were unsuccessful [31-33].

**Methods and Results.** We extracted chondrules from two separate pieces of Allende and processed multichondrule fractions for Pb isotopic analyses

using two different approaches. Multiple fractions were aggressively leached at the Geological Survey of Canada, resulting in 15 highly-radiogenic Pb analyses from the residual portions. A single fraction was subjected to a progressive dissolution procedure at Copenhagen University that yielded 6 widely-spaced co-linear points in Pb-Pb space.

We have combined the two Pb-Pb data sets for chondrules from Allende to derive an integrated data array that defines an absolute Pb-Pb age of  $4565.45 \pm 0.45$  Ma (Fig. 1). The precision reflects the highly-radiogenic nature of data set A (highly-leached residues, Geological Survey of Canada) combined with the large spread of points in data set B (progressive dissolution, University of Copenhagen). The robustness of this age is reinforced by the extrapolation of the line through the accepted estimate of the Solar System primordial Pb isotopic composition [34] indicating that terrestrial Pb contamination was successfully removed. This age is inferred to represent the time of final crystallization of the chondrules sampled from the CV chondrite Allende.



**Fig. 1.** Pb-Pb isochron for the Allende chondrules.

**Discussion.** Formation of chondrules after CAIs is supported by the presence of relict CAIs inside chondrules [4, 35], the presence of chondrule-like igneous rims around some CAIs [36], and the volatility fractionated (group II-like) trace element patterns exhibited by some chondrules [37]. The absolute age presented here indicates an age difference of  $1.66 \pm 0.48$  Ma between CAIs and chondrules from CV chondrites. This age difference is consistent with their relative ages inferred from the differences in the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios [6] and, therefore, supports a chronological significance of  $^{26}\text{Al}$ - $^{26}\text{Mg}$  systematics in general. We conclude that high-precision magnesium isotope measurements of

CAIs and chondrules from primitive chondrites (e.g., CR2, CO3.0, Acfer 094) can be used to constrain the duration of CAI- and chondrule-forming events and the life-time of the protoplanetary disk.

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