RELATIONSHIP BETWEEN CAIS AND CHONDRULES: WHAT WE CAN LEARN FROM A CHONDRULE-CAI HYBRID IN THE ALLENDE CV3 METEORITE. S. S. Russell[1], R. Armytage[2], J-D. Bodenan[1,3], I.A. Franchi[3], T. Jeffries[1], J. Spratt[1] and N.A. Starkey[3], [1]Department of Earth Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK (sarr@nhm.ac.uk), [2]Department of Earth and Atmospheric Sciences, University of Houston, Houston 77204, TX, USA, [3]Planetary and Space Sciences, Open University, Milton Keynes MK7 6AA, UK.

Introduction: Chondrules and calcium aluminium-rich inclusions are important components of chondrites. Absolute age dating suggests that CAIs formed early in solar system history. Chondrules began to form at around the same time and continued for several millions of years [1]. These two components were then mixed prior to the final assembly of the parent body. However examples of CAIs and chondrules that apparently were heated together are rare [2]. Where were the CAIs during the chondrule forming event? Clues may be provided by studying the rare examples of compound objects that have features of both chondrules and CAIs.

We report on the mineralogy, petrology, oxygen and silicon isotope composition of a hybrid compound CAI-chondrule from the Allende (CV3) meteorite, called Allende 04d that may provide clues about the relationship between these two types of object.

Techniques: The object was separated from the Allende meteorite at the University of Oxford. Part of the chondrule was dissolved for bulk Si isotope measurements by Nu Plasma HR MC- ICP-MS and the remainder mounted and polished. This portion was used for mineralogical and petrological analysis using the Zeiss Evo 15LS scanning electron microscope and Cameca SX100 electron microprobe at the Natural History Museum. The sample was then analyzed for high precision oxygen isotopes using the Open University Cameca NanoSIMS 50L using the methodology of Starkey and Franchi 2013 [3]. A 5x5µm spot size was used for all O isotope analyses.

Results: *Petrological and Geochemical Description.* The object is composed of three petrologically distinct regions. Region 1 (lower left of Figure 1) is composed of blocky anorthite laths up to 100 microns long, surrounded by Al-rich diopside. Phenocrysts of spinel are common. The spinel can be up to around 50 microns across and is often partially resorbed. Spinel is strongly zoned with respect to iron content, with values of FeO up to 19% recorded. Abundant smaller olivine grains (Fo_{91}) are also present. Region 2 (red circular feature at mid- right hand side of Figure 1) has a similar texture to type 1 porphyritic olivine chondrules. Region 3 (upper third and lower right) is composed of skeletal radiating plagioclase and diopside and abundant olivine phenocrysts ($Fo_{83\text{-}93}$)and this may have formed from a mixing between material similar to that in Regions 1 and 2.

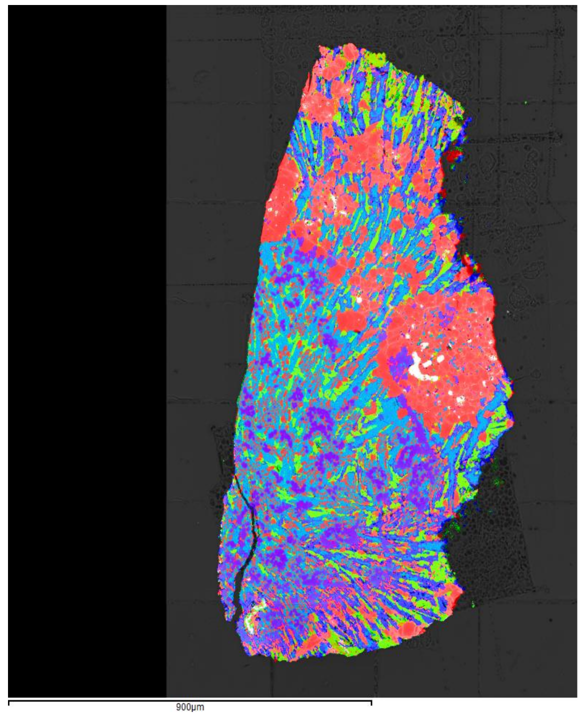

Figure 1. An elemental map of Allende 04d. The size of this fragment is approximately 1mm x 0.5 mm across. Red = Mg, Blue=Al, and Green= Ca. The "porphyritic chondrule" portion of the object show up as red and the "CAI" portion is closer to purple in this figure.

Silicon isotopes. Armytage et al. [3] previously reported silicon isotope compositions for 11 Allende chondrules and 4 Mokoia chondrules to an external reproducibility of <0.15‰. Allende 04d was part of this dataset and the $\delta^{30}Si$ for 04d is -0.71 ‰. This was the lightest, with respect to Si isotopes, of the chondrules measured in their study (the full range was -0.71 to -0.1 ‰ [4].

Oxygen isotopes Oxygen isotopes were measured in olivine and spinel in the "CAI-like" and "chondrule-like" portions of 04d and the results are shown in Figure 2. The data form an array that lies between the CCAM line and the Young and Russell line [5]. For olivine, the oxygen isotopes fall into two distinct groups. Olivine in the porphyritic portion is indistinguishable from the radial region and has an average $\delta^{18}O$ of –2.5 ‰ and $\Delta^{17}O$ of -3.24 ‰ (2SE = 0.44‰).In the CAI portion the olivine is heavier, with an average $\delta^{18}O$ of +1.9 ‰ and a slightly heavier $\Delta^{17}O$ of -2.49‰ (2SE = 0.71‰). For spinel, the $\delta^{18}O$ in the chondrule portion ranges widely from -3.5‰ to -34‰ ($\Delta^{17}O$ from -4.5 to -17‰). Spinel in the CAI portion varies in oxygen isotopic composition along the CCAM line although the range is smaller than for the chondrule spinel, and the lightest value recorded has $\delta^{18}O$ = -17.9‰.

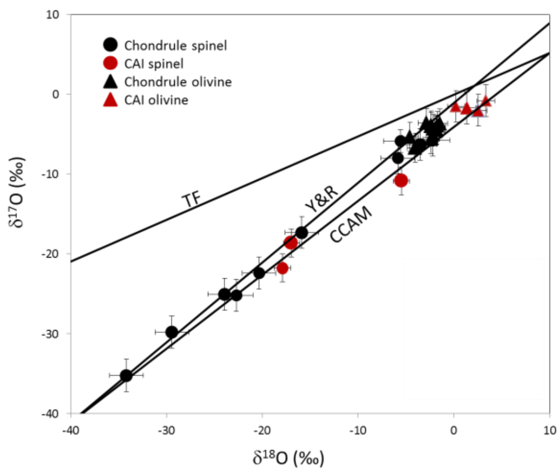

Figure 2. A three oxygen isotope plot of spinel and olivine in Allende 04d. Errors are 2σ.

Discussion: *Composition and Texture of the original CAI.* The object is a compound chondrule composed of a chondrule portion and a heavily altered CAI-like portion. The bulk chemical composition of the CAI region is similar to a Type C or spinel-rich inclusion. Most CAIs measured to date are enriched in the heavy isotopes of silicon [e.g. 4, 6, 7]. The light silicon isotopes recorded in this object point to the CAI portion originally being a fine- grained fluffy condensate, as such inclusions can have light Si isotope compositions [7], and so a fine-grained spinel-rich CAI is the most likely CAI precursor for this object.

History of the Object. We infer the following history for this object: (1) A fine grained spinel-rich CAI forms from a refractory-depleted reservoir that has some Ca removed. Most likely the CAI formed in a ^{16}O rich environment as do most CAIs; (2) The CAI interacts with the oxygen in the nebular gas to produce heavier bulk oxygen isotope values. Because the oxygen in olivine in the CAI portion and chondrule portions are distinguishable, the oxygen isotope exchange must have occurred in the nebula, before the event that caused the two objects to melt together and become conjoined. The oxygen isotope exchange also affected spinel but to a lesser extent; (3) the porphyritic chondrule formed. The relative timing between chondrule formation and CAI formation cannot be determined petrographically since they formed separately; (4) the porphyritic chondrule and the fine-grained CAI were melted together to produce a compound object and the radial textured part of the object was formed at this time; (5) the object accreted onto the Allende parent body and experienced parent body alteration, and it was probably during this process that Fe was incorporated into the spinel.

Puzzle of the Missing Melilite. Of the several compound CAI-chondrule objects so far reported, all of the original CAIs seem to have a bulk composition approximately matching that of Type C CAIs or spinel-rich inclusions, with a mineralogy typically composed of anorthite, diopside and spinel [e.g. 2,7]. This is a problem that MacPherson *et al.* have referred to as the "Puzzle of the Missing Melilite"- CAI –chondrule compound objects tend not to contain melilite, , although this is a common mineral in CV3 CAIs [8]. While some CAIs were apparently present in the chondrule forming region, this seems limited to a specific CAI type. This is especially puzzling considering that the high abundance of volatile elements in chondrules points to a very high dust/gas ratio during chondrule formation, which in turn suggests that accretion was associated with chondrule formation [9]. The absence of most CAI types during chondrule formation, and the rarity of CAI-chondrule compounds, suggests that the majority of the CAI population may have been mixed in to the CV3 parent body during an event that postdated their original accretion.

References:

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Acknowledgement: NanoSIMS access was provided through UKCAN (STFC grant ST/I001964/1).