MICRODISTRIBUTION OF OXYGEN ISOTOPES IN UNEQUILIBRATED ENSTATITE CHONDRITES.

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Introduction: Enstatite chondrites are important for constraining conditions and processes in the protoplanetary disk and for understanding the accretion of the terrestrial planets. They are among the most reduced solar system materials as indicated by their unique mineral assemblages and compositions [1, 2]. Their whole rock stable (O, Cr, Ti, Ni and Zn) isotope compositions are markedly similar to those of the Earth-Moon [3-5] and the surface chemistry of Mercury suggests reduced E chondrite-like precursors [6]. Thus, the E chondrites may represent the materials that were present in the source regions during accretion of the terrestrial planets. We previously studied the petrology and oxygen isotope compositions of chondrules in the Sahara 97096, Y 691, Kota- Kota and LEW 87223 E3 chondrites and showed that they define a line, termed the enstatite chondrite mixing (ECM) line [7, 8], which is indistinguishable from the primitive chondrule mineral (PCM) line defined by Acfer 094 chondrules [9]. Here we report new, high precision, *in situ* oxygen isotope analyses of 30 clasts (chondrules, refractory inclusions and metal nodules) in the highly primitive ALH 81189 (and paired ALH 85159) EH3 and, to our knowledge, the first oxygen isotope analyses of individual clasts in an EL3 (MAC 88136) chondrite.

Methods: We selected 21 clasts (chondrules, fragments, metal nodules, refractory inclusions) from thin section ALH 81189, 3 (EH3), 9 clasts from ALH 85159, 5 (paired with ALH 81189) and 13 clasts from MAC 88136, 37 (EL3) for oxygen isotope analysis. Element maps for all sections, BSE images of each clast and major mineral compositions (WDS) were collected using a combination of the Cameca SX 100 electron probe (AMNH) and the JEOL DSM 950 SEM (CUNY). Oxygen isotopes silicates were analyzed *in situ*, using the Cameca IMS 1280 ion microprobe at the WiscSIMS laboratory. The goal was to measure six grains (olivine and pyroxene) in each clast, if grain size allowed, to achieve a representative average and test for internal homogeneity within each clast. The analytical procedure was similar to that described in [10] using three Faraday cups on the multi-collection system for high precision oxygen three isotope analyses. A Cs+ primary beam of ~ 2 nA focused to a 12 μm diameter was used. Average external reproducibility of bracketing standard analyses (2SD) were ~0.2 ‰ for $\delta^{18}O$ and 0.3 ‰ for $\delta^{17}O$ and $\Delta^{17}O$.

Results: *Petrology*. The clasts we studied from ALH 81189 and paired ALH 85159 included 20 porphyritic pyroxene (PP), 1 PP with Fe-rich pyroxene, 2 porphyritic pyroxene-olivine (POP), 2 porphyritic olivine (PO) chondrules, 1 barred pyroxene, 1 AOA, 1 diopside-plagioclase fragment and 1 metal-rich nodule containing enstatite (En_{98}). From MAC 88136 we studied an unusually large (>1mm) diopside-rich chondrule, a silica-pyroxene chondrule, a radial pyroxene and 7 PP's and 3 metal nodules with enstatite laths.

As typical of EH3 and EL3, most chondrules are dominantly enstatite and can be considered type IB. PP is the most common textural type. The PP chondrules we studied contain near-endmember enstatite ($En_{>98}$). One PP in ALH 81189 was dominated by Fe-rich pyroxene ($Wo_{0.1}En_{73\text{-}83}$). Unlike most other chondrite groups, olivine is minor in the E3 chondrites. It occurs mainly as poikilitically enclosed in enstatite in the pyroxene-rich chondrules, but we also identified rare PO chondrules and isolated olivine mineral fragments (Fo_{98}) up to 300 μm in size in ALH 81189.

Several unusual clasts were also studied including a diopside–plagioclase clast in ALH 81189 unlike any chondrule or fragment previously described in E3 chondrites. It is irregular in shape, ~300 μm across and composed mainly of laths of diopside ($Wo_{44.8}En_{54.3}$) having 2.5% Al_2O_3 and 1.5 TiO_2 and plag ($An_{71.9}Ab_{20.9}$), with minor enstatite ($Wo_{0.6}En_{97.1}$) and silica. The AOA we studied is an irregular-shaped inclusion consisting of olivine ($Fo_{99.3}$) surrounding nodules of Ca-pyroxene and anorthite.

The diopside-rich chondrule in MAC 88136 is ~50% diopside ($Wo_{46.4}$ $En_{53.2}$) occurring with enstatite ($Wo_{0.7}$ $En_{98.9}$), silica and FeNi metal. Metal nodules in EL3 chondrites (also called metal-silicate intergrowths) have been a target of controversy as to whether they are primary nebular-formed objects or products of impact melting. They contain laths of enstatite (~En_{98}) intergrown with metal.

Oxygen isotopes. Average oxygen isotope ratios for each clast are plotted in Fig. 1. The average values for each clast was used since most of the chondrules are internally homogeneous with respect to their oxygen compositions. Interestingly, the data from the chondrules and other clasts in ALH 81189 and MAC 88136 form a trend that coincides with the slope~1 PCM line, with most clasts clustering at the intersection of the PCM with the terrestrial fractionation (TF) line (Fig. 1). However, 5 chondrules from ALH 81189 and 2 from MAC 88136 appear to form a resolvable second trend above and possibly parallel to the PCM line (indicated by a green dashed line in Fig. 1.)

The data from ALH 81189 (EH3) and the more limited data set from MAC 88136 (EL3) overlap and show a similar distribution. $\Delta^{17}O$ for ALH 81189 and 85159 chondrules range from –1.4 to 1.3‰ and for MAC 88136 the range is –0.6 to 1.3‰.

One PP chondrule in ALH 81189 has a relatively ^{16}O-rich composition of $\delta^{18}O$ = 2.3‰, $\delta^{17}O$ = –0.2‰. Silica from the silica-rich and diopside-rich chondrules in MAC 88136 are also plotted. They are compositionally similar plotting on the TF line at $\delta^{18}O$ = 8.7‰ and 8.3‰, respectively. Olivine in the AOA from ALH 81189 is ^{16}O-rich with $\delta^{18}O$ = –46.5‰, $\delta^{17}O$ = –48.0‰, similar to AOAs and refractory inclusions in other chondrite groups (Fig. 2). Aside from the AOA, there is no clear relationship between oxygen isotope composition and chondrule type or textural setting.

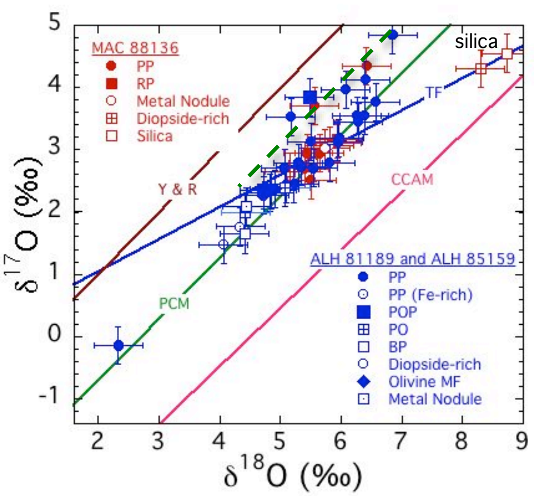

Fig. 1 Oxygen 3-isotope diagram showing average oxygen isotope ratios for clasts in ALH 81189, ALH 85159 and MAC 88136. Most data plot along the primitive chondrule mineral (PCM) line [9], mostly clustering at the intersection with the terrestrial fractionation (TF) line. Y & R - Young and Russell, CCAM - carbonaceous chondrite anhydrous mineral. A green dashed line was drawn parallel to the PCM line through seven E chondrite clasts that lie above the PCM, possibly forming a second trend.

Discussion and Conclusions: Whole rock oxygen isotope compositions for E chondrites plot along or close to the TF line on a three isotope diagram [e.g., 11]. However, the individual chondrules from both EH3 and EL3 chondrites show a trend along the PCM line (Fig. 1), consistent with our previous studies of chondrules in E3 chondrites [7, 8] and similar to the findings of [12]. The data indicate a clear distinction between chondrules in the E chondrites and those in O, R and most C chondrite groups. The PCM line is interpreted to be a mixing line of the primary oxygen isotope reservoirs of solids that accreted to form the terrestrial planets [9]. The trend in E3 chondrule oxygen was also interpreted to result from reactions between ^{16}O-rich olivine-rich chondrule melts and ^{16}O-poor SiO-rich gas [12]. Chondrule oxygen isotopes in other chondrite groups may represent mixing of different precursors and/or modification by secondary alteration, not observed in E3 chondrules.

Seven of the chondrules analyzed form a separate trend above but parallel to the PCM. These oxygen isotope compositions overlap those of some OC chondrules [10] suggesting limited mixing of materials between the different oxygen reservoirs. The overlap in oxygen isotopes between EH3 and EL3 chondrules suggest they share similar precursors but their mineral compositions indicate different degrees of reduction [1, 2], suggesting different nebular environments and/or separate, possibly multiple [e.g., 13], parent bodies.

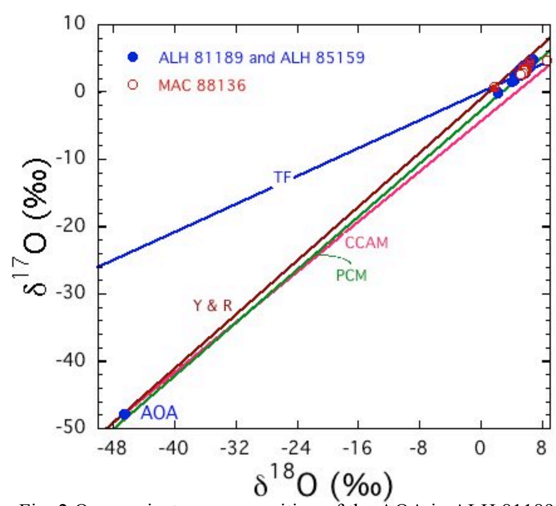

Fig. 2 Oxygen isotope composition of the AOA in ALH 81189.

References: [1] Keil K. (1968) *JGR,* 73, 6945-6976. [2] Weisberg M.K. and Kimura M. (2012) *Chem. Erde, 72,* 101-115. [3] Javoy M. (1995) *GRL,* 22, 2219-2222. [4] Warren P.H. (2011) *EPSL,* 311, 93–100. [5] Paniello R. et al. (2012) *Nature* 490, 376-379. [6] Nittler L.R. et al. (2011) *Science* 333, 1847-1850. [7] Weisberg M.K. et al. (2011) *GCA,* 75, 6556-6569. [8] Weisberg M.K. et al. (2010) *LPS XI,* Abstract #1756. [9] Ushikubo T. et al. (2012) *GCA, 90,* 242-264. [10] Kita N.T. et al. (2010) *GCA, 74,* 6610–6635. [11] Weisberg M.K. et al. (1995) *LPS XXVI*, 1481-1482. [12] Tanaka R. and Nakamura E. (2017) *Nat. Astron.,*1, 0137. [13] Weyrauch M. et al. (2018) *Meteoritics & Planet. Sci.* 53, 394-415.