OXYGEN ISOTOPES OF ALUMINUM-RICH CHONDRULES FROM UNEQUILIBRATED ENSTATITE CHONDRITES. Y. Guan, L. A. Leshin, G. J. MacPherson, 1Department of Geological Sciences, 2Center for Meteorite Studies, Arizona State University, Tempe AZ 85287-1404, USA. 3Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington DC 20560-0119, USA. (yg@asu.edu).

Introduction: Al-rich chondrules, which commonly consist of primary anorthite or Al-rich glass, spinel, Al-rich diopside, and olivine, are rare in most unequilibrated enstatite chondrites (UECs). In a previous study of calcium-aluminum-rich inclusions (CAIs) in UECs [1], we incidentally analyzed the oxygen isotopic composition of an Al-rich chondrule from EET 87746 (EH3). The data showed that its oxygen isotopes fall outside the typical range for UEC ferromagnesian chondrules. In this report, we have measured oxygen isotopic compositions of additional Al-rich chondrules in UECs, with the goals of determining their relationship to UEC ferromagnesian chondrules and comparing them with Al-rich chondrules in unequilibrated ordinary chondrites (UOCs) and with CAIs in general.

Samples and Experimental: The Al-rich chondrules were identified from elemental X-ray maps of polished UEC thin sections by using a scanning electron microscope (SEM). One of the Al-rich chondrules was previously described [1]: E4642-1 from EET 87746 is ~100 μm in diameter and consists of euhedral spinel (up to ~20x50 μm), aluminous diopside, and two types of glass (CaO ~9-12%, Na2O ~3-4%; and CaO <2%, Na2O ~10-11%). The Al-rich chondrules L2003-1 and L2003-2 are from LEW 87220 (EL3). L2003-1 is ~420 μm in size and dominated by Na-Ca-rich glass that encloses dendritic Al-rich diopside laths. It also contains spinel, olivine, and enstatite grains (Fig. 1). L2003-2, a porphyritic chondrule of ~250 μm in diameter, is mainly composed of anorthite and enstatite, with minor amount of spinel and Al-rich diopside. E4640-2 is a small (~100 μm in diameter) compact pyroxene-anorthite Al-rich chondrule from EET 87746, with Al2O3 in diopside up to 33 wt%.

In-situ oxygen isotope analyses of the Al-rich chondrules were carried out using the Cameca IMS 6f ion microprobe at ASU. A 0.2-0.34 nA beam of Cs+ was focused into a spot of ~20 μm in diameter in aperture illumination mode. Secondary ions were accelerated to -9 keV and collected by peak-jumping into either a Faraday cup (18O) or electron multiplier (16O and 17O) at a mass resolving power of ~6000, easily resolving the 16OH interference on 18O. Uncertainties on individual analyses, taking into account the variation on repeated analyses of the standard, are ~3‰ (2σ). The magnitude of matrix effects is small (~1-2‰) under our analysis conditions. No correction for such effects has been made.

Results and Discussion: The oxygen isotope results from three Al-rich chondrules, plus data from the one analyzed previously [1], are plotted in Fig. 2. Shown for reference on the plot are the oxygen isotopic compositions of bulk ferromagnesian chondrules from enstatite chondrites [2].

The oxygen isotopic compositions of the four UEC Al-rich chondrules spread over a range of ~10‰. Data from the pyroxene-anorthite Al-rich chondrule E4640-2 falls within the range of the ferromagnesian chondrules of enstatite chondrites, whereas the other three Al-rich chondrules plot to the 18O-enriched direction, along the extension line defined by the ferromagnesian chondrules. E4642-1 is the most 18O-enriched Al-rich chondrule, with δ18O = -5‰ and δ17O = -3‰. All the data points from the Al-rich chondrules roughly determine a correlation line of slope 0.7±0.1, similar to the one defined by bulk ferromagnesian chondrules [2].

The observation that both Al-rich and ferromagnesian chondrules in UECs are approximately distributed on a single isotopic mixing line indicates that they are genetically related to each other. The oxygen isotopes of UEC CAIs [1, 3], however, do not fall on the same mixing line. Neither can UEC CAIs be linked to ferromagnesian chondrules of enstatite chondrites through the CCAM or Young and Russell lines [1]. There is no compelling evidence that the chondrule mixing line of slope 0.7±0.1 in enstatite chondrites might form from overprinting of a slope ~1 mixing line with mass-dependent fractionation processes. Therefore, the UEC CAIs apparently do not represent the 18O-rich end-member of the UEC chondrule mixing line. The Al-rich chondrules in UECs cannot be mixing products of CAIs and ferromagnesian chondrules. Similar relationship between Al-rich chondrules, ferromagnesian chondrules, and CAIs was also observed in ordinary chondrites [4].

Internal isotopic heterogeneities among minerals were exhibited in the Al-rich chondrules L2003-1 and L2003-2. In general, spinel and olivine are more 18O-enriched than other mineral phases, such as Al-rich diopside or anorthite. Because of the large uncertainties of the data and possible matrix effects, the origin
of these internal variations cannot be unequivocally determined. They could be produced either by mass-dependent isotopic fractionation or by partial isotopic exchange with an external reservoir, either in the nebular or on the parent body.

The entire oxygen isotopic range (~10‰) of UEC Al-rich chondrules observed in this study is significantly smaller than that of UOC Al-rich chondrules (~20‰) [4]. This could merely be a sampling bias due to the smaller dataset of this study. On the other hand, it might be another indication of the genetic relationship between Al-rich and ferromagnesian chondrules in enstatite chondrites. It has been known that the ferromagnesian chondrules in enstatite chondrites have a very restricted oxygen isotopic region, which is regarded as an indication of close approach to equilibrium between chondrules and the ambient nebular gas for enstatite chondrites [5]. Isotopic exchange at similar conditions would produce a narrow oxygen isotopic range for Al-rich chondrules as well. Furthermore, a larger degree of equilibration with the ambient nebular gas (higher temperature?) may well explain the difference in Al-Mg systematics between UEC and UOC Al-rich chondrules: In UOCs, about one third of those Al-rich chondrules measured contain $^{26}$Mg excesses from the $in situ$ decay of $^{26}$Al [6], with inferred initial $(^{26}\text{Al}/^{27}\text{Al})_o$ ratios ranging from $\sim5\times10^{-6}$ to $\sim1\times10^{-5}$. In UECs, out of the 14 UEC Al-rich chondrules analyzed so far [7, 8, and unpublished data], only one was found containing resolvable $^{26}$Mg excesses from the $in situ$ decay of $^{26}$Al, with a $(^{26}\text{Al}/^{27}\text{Al})_o$ ratio of $\sim5\times10^{-6}$ [7].

**Conclusions:** The oxygen isotopic compositions of UEC Al-rich chondrules define a mixing line of slope $\sim0.7\pm0.1$ that extends to the $^{16}$O-enriched direction from the ferromagnesian chondrule field of enstatite chondrites, suggesting that they are genetically related to ferromagnesian chondrules, but not to CAIs in enstatite chondrites. Therefore, similar to their UOC counterparts, UEC Al-rich chondrules were not simple mixtures of ferromagnesian chondrules and CAI material.


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**Fig. 1** Backscatter electron image of the Al-rich chondrule L2003-1 from LEW 87220. The chondrule is about 420 µm in diameter.

**Fig. 2** Oxygen isotopic compositions of Al-rich chondrules in unequilibrated enstatite chondrites. Data points are color-coded for each individual chondrule. E4642-1 –blue; L2003-1 –red; L2003-2 –brown; E4640-2 –black. Triangle –spinel; Circle –anorthite or glass; Square –diopside; Cross –olivine.