

HALOGEN ABUNDANCES IN THE EARLY SOLAR SYSTEM: HALOGENS IN CHONDRULE PRECURSORS, AND MODIFICATIONS DURING AND AFTER CHONDRULE FORMATION

E. Baker¹, R. H. Jones¹ and J. Villeneuve², Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK (edward.baker@manchester.ac.uk). ²Centre for Petrographic and Geochemical Research (CRPG), Nancy, France

Introduction: In the nascent solar nebula, halogens were likely present as H-[F,Cl,Br,I] species in the gas phase. As the nebula cooled, halogen-bearing phases condensed, with less refractory phases condensing further from the Sun. Estimates of 50% condensation temperatures (T_c) for the halogens at 10^{-4} bar range from 390 K for iodine as KI to 674 K for F as fluorapatite [1–3]. This T_c range maps to a wide range of heliocentric distances for halogen carrier phases and determines the original halogen inventory that we aim to constrain for the terrestrial planets. Through examining halogen abundances in chondrules, we can investigate the halogen-bearing species present in the protoplanetary disk. However, solid chondrule precursor materials for chondrules are difficult to identify. Models of chondrule formation call for an intense heating event: this heating and cooling step modifies the concentration of halogens found in chondrules.

We are investigating the behaviour of halogens in chondrule melts to assess whether the halogen concentrations observed in chondrules are representative of the halogen content of chondrule precursor solids. Following initial melting, halogens will simultaneously be concentrated into the melt during crystallization, as halogens are incompatible in most silicate phases, and they will also be depleted by evaporative loss from the chondrule surface; halogens may also condense back into the chondrule as it cools.

Additionally, halogens may partition into phases such as sulfides within the chondrule, thus retaining halogens within the chondrule. To reconstruct the original halogen abundance, we aim to quantify these competing processes with new SIMS data on halogen abundances in mesostasis glass. We focus the study on chondrules from enstatite chondrites as well as one CR chondrite.

Methods: We have analyzed mesostasis in 50 chondrules from Sahara (SAH) 97072 (EH3), Larkman Nunatak (LAR) 12156 (EH3), LAR 12252 (EH3), Dominion Range (DOM) 14021 (EH3), Qingzhen (EH3), Elephant Moraine (EET) 83322 (EH3) and EET 92062 (CR2). Glass compositions, including Cl, were measured using a Cameca SX5 FEG electron probe at the University of Oxford. Halogen (F, Br, Cl, I) and sulfur concentrations were

measured using a Cameca IMS 1280-HR SIMS at CRPG, Nancy, France.

Results: The mean values of our preliminary data for halogens in chondrule glasses are (1σ standard deviation in brackets): F = 320 (484), Cl = 3,900 (7116), Br = 21 (35), I = 370 (1605) $\mu\text{g}\cdot\text{g}^{-1}$, see Figure 1. Abundances of Cl are similar to those measured by [4–7]; however, there are few literature data for F or the heavier halogens, Br and I [8]. Relatively large standard deviations are caused by long tails to high concentrations. Preliminary data for chondrule glass in the CR chondrite EET 92062 shows that it has lower Cl but similar F, Br and I compared to EC chondrule glasses.

Discussion: Our data show a significant range of mesostasis halogen concentrations both within and between different enstatite chondrites. This could point to either variability arising during chondrule formation, or heterogeneous secondary processes on the parent body. The spread of data, 3 orders of magnitude, could suggest a role for parent body processes. However, here we focus on effects related to chondrule formation. Some chondrules show a radial depletion in Br and Cl, i.e., higher values in the centres of chondrules, which we can explain as diffusively controlled evaporation. All halogens are incompatible in silicate crystals [9; 10], so chondrule crystallization is not likely to significantly change the relative abundances, although crystallization will increase the absolute abundance in the melt [11; 12].

In comparison to chondritic (bulk) halogen ratios, our data show that both Br/Cl and I/Cl are super-chondritic in chondrule glass. The gradient of our Br/Cl data is only ~10% greater than the bulk Br/Cl ratio reported by [13], however, the I/Cl slope is ~200 times steeper (more super-chondritic) than that of [13]. If representative of the precursor phases, these super-chondritic ratios imply low T_c 's because Br- and I-containing phases have lower T_c 's than Cl and F. F/Cl data cover a wide range of super- to sub-chondritic values. F concentrations mostly do not vary radially within the chondrules, possibly because F is most compatible in silicate minerals, and diffuses most quickly, in which case F would reach equilibrium first. The F/Cl variation is then explicable by the range (centre to edge), observed in Cl in individual chondrules.

We suggest that another effect, sometimes called scavenging, could occur during chondrule formation. At reducing conditions, S^{2-} is the dominant sulfur species in silicate melts. S^{2-} becomes less soluble with decreasing temperature [14; 15], resulting in precipitation of (sub)micron size sulfide blebs throughout mesostasis glass. Iodine, which is the most incompatible halogen in silicate melt [16], is also the most chalcophile [17]. Consequently, I may be most concentrated into sulfide phases. Scavenging of I would reduce the rate at which the chondrules' I inventory will degas. As a result, the mesostasis redox state could control the ability of the more strongly chalcophile elements to degas.

At this stage of our study, we can draw three conclusions. First, I/Cl and Br/Cl are found in chondritic or super-chondritic ratios in the chondrules analysed, suggesting low ambient temperatures (~400 K) in the enstatite chondrite formation region. Secondly, some chondrules show a significant radial depletion of Br and Cl, probably indicating diffusively controlled evaporative loss immediately following formation, while the chondrule is cooling and (partially) molten. Finally, the intra chondrite variance suggests that halogen abundances may have been modified by heterogeneous parent body effects, which we plan to investigate further.

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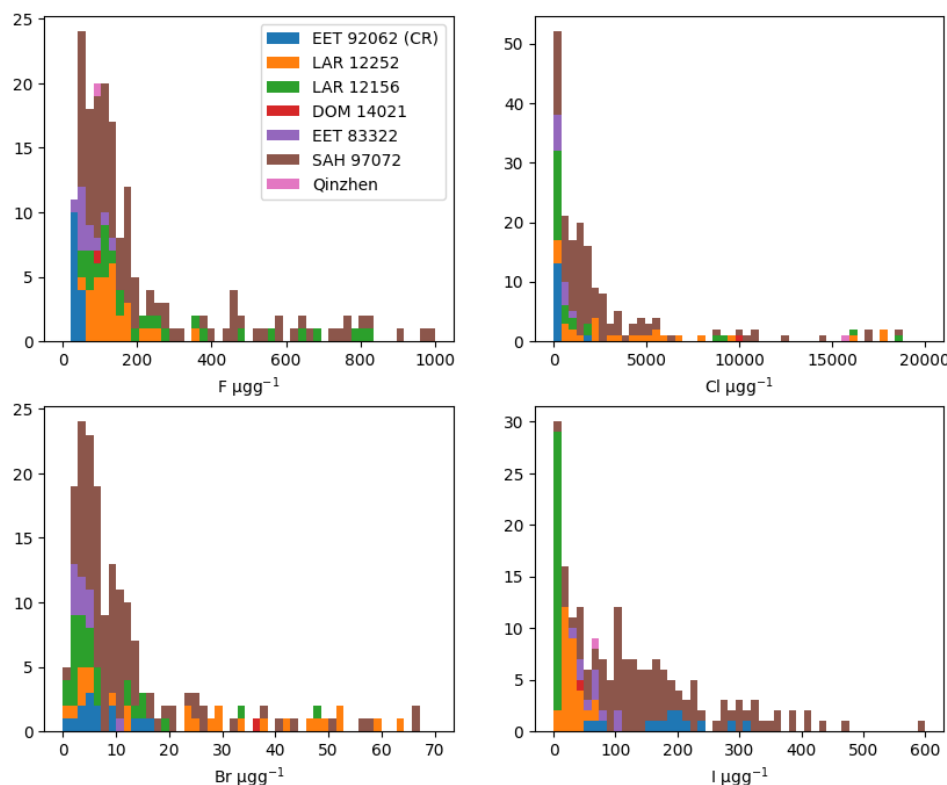


Figure 1: Stacked histograms of our SIMS halogen data taken from mesostasis glass in enstatite chondrites and the CR chondrite, EET 92062. There is significant overlap between different enstatite chondrites with the intra chondrite variance greater than the inter chondrite variance. Maximum values are not shown; max F = 2,900, max Cl = 65,000, max Br = 210, max I = 1,600 $\mu\text{g}\cdot\text{g}^{-1}$.