Ion microprobe studies of REEs in fine-grained inclusions in the Efremovka CV3 meteorite

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Fractionation among rare earth elements (REEs) sometimes found in refractory inclusions (CAIs) suggests gas-dust separation in the early solar nebula at high temperatures. Hence, REE fractionation patterns would give important information about the conditions of CAI formation regions.

An ultrarefractory nodule, *Himiko*, was found in a fine-grained CAI, EFG-1, in the Efremovka CV3 chondrite (Kimura et al., 2003). We performed REE analyses using SIMS for *Himiko*, its host inclusion EFG-1, and some other fine-grained CAIs in Efremovka. We also performed thermodynamic condensation calculations using simple assumptions and compared the results with the observed REE patterns. The results of *Himiko* and EFG-1 are also presented briefly in Uchiyama et al. (2008). Here we present more REE data on fine-grained inclusions from Efremovka and discuss their formation conditions in more detail.

We performed ˜5 micrometer spot analyses for *Himiko* using a CAMECA NanoSIMS 50 at the Ocean Research Institute, the University of Tokyo. We used an O^- primary beam with an intensity of ˜1nA. Mass resolution was set to ˜1000 with entrance and aperture slits full open. An energy filtering method was used for the REE analyses with ˜40eV energy window and -60eV energy offset, which greatly reduced contributions of complex molecular ions. Contributions of REE monoxide ions were corrected using predetermined production ratios of ($REEO^+/REE^+$). We measured 20 peaks using 5 EM detectors and 6 different magnetic fields to determine concentrations of all REEs, Ba, Hf and Ca. NIST 610 standard was used to determine sensitivity factors of REEs relative to Ca. We also used a synthetic REE-doped glass for positioning of REE peaks. We tried 6 analyses for *Himiko* and the last two analyses for ZrO_2-bearing phases were successful.

Himiko shows a HREE-enriched ultrarefractory (UR) pattern, but REE concentrations of are extremely high (more than 20000 x CI for Lu and Er, and more than 200 x CI for LREEs) and fractionation among HREEs are also very large (Lu and Er are more than 10 times more enriched than Gd). A condensation calculation suggests that *Himiko* was formed and separated from the gas at higher than 1700K at a total pressure (P_{tot}) of 10^{-4} atm. Hence, the most likely host of REEs in *Himiko* is ZrO_2 (condensation temperature =1741K at P_{tot} =10^{-4} atm; Lodders, 2003).

For the ordinary part of EFG-1 and for the other fine-grained inclusions, REEs were analyzed with ims-6f. An O^- primary beam, ˜50 micrometer in diameter and ˜10nA intensity for the former and 20-30 micrometer in diameter and ˜1nA intensity for the latter, was used. An energy filtering method, using ˜30eV energy window and -60eV energy offset, was applied at a mass resolution of ˜300. The ordinary part of EFG-1 shows a HREE-depleted pattern, but LREEs are also largely fractionated, in contrast to typical Group II patterns. Based on a condensation calculation, gas-dust separation must occur at 1500-1550K. Most of the other CAIs show typical Group II patterns, implying the gas-dust separation temperatures of 1600-1650K (at P_{tot} =10^{-4} atm).

The present results suggest that gas-dust separation occurred at a wide range of temperatures from ˜1500K up to higher than 1700K (at 10^{-4} atm) in the formation regions of fine-grained inclusions. The fact that *Himiko* and its host EFG-1 were found together in a single CAI suggests that effective material flow and mixing occurred in the CAI formation regions. The REE patterns of *Himiko* and its host CAI, however, are not exactly complimentary with each other, and more study is required for full understanding of their relations and formation conditions.

References: Kimura et al. (2003), Abstract for NIPR Symp., Japan. Uchiyama et al. (2008), LPSC #1519. Lodders (2003), ApJ 591, 1220-1247.