Final Report: NAG5-9789 **PI: Kevin D. McKeegan**

"Isotopic investigations of Nebular and Parent Body Processes with a High Sensitivity Ion Microprobe"

NASA NAGW-9789 supported the development of the CAMECA ims 1270 ion microprobe at UCLA for applications in cosmochemistry. The primary investigations centered on measuring the microscopic distributions of key isotopic abundances in primitive meteoritic materials as a means of constraining the nature of important thermal and chemical processes in the solar nebula and the timescales associated with those processes. Our prior work on oxygen isotope anomalies in a wide variety of meteoritic materials had led us to a view of a spatially heterogeneous nebula, and in particular, a restricted region for CAI formation that is characterized by ^{16}O-rich gas [e.g., \McKeegan, 1998 #420; Fagan, 2001 #915; Guan, 2000 #914; Krot, 2002 #1279]. Because of its production of CAIs in the energetic local environment near the protosun, the existence of a natural transport mechanism *via* bipolar outflows, and a general astrophysical plausibility, we were attracted to the fluctuating X-wind model which had been put forward by Frank Shu, Typhoon Lee, and colleagues [Shu, 1996 #176; Shu, 1997 #378; Shu, 2001 #1326]. With our collaborators, we undertook a series of investigations to test the viability of this hypothesis; this work led directly to the discovery of live ^{10}Be in CAIs (McKeegan et al., 2000) and a clear demonstration of the existence of ^{16}O-rich condensates, which necessarily implies an ^{16}O-rich gaseous reservoir in the nebula [Simon, 2002 #1321; Krot, 2002 #1279]. Both of these observations fit well within the context of X-wind type models, i.e. formation of CAIs (or condensation of their precursors) in the reconnection ring sunward of the inner edge of the accretion disk, however much work remains to be done to test whether the physical parameters of the model can quantitatively predict not only the thermal histories of CAIs but also their radioactivity [Lee, 1998 #802; Gounelle, 2001 #1327].

The issue of spatial heterogeneity in the nebula, central to the X-wind model, is also at the heart of any chronology based on short-lived radioisotopes. In this work, we followed up on strong hints for presence of extremely (53 day) short-lived ^{7}Be, and have prepared a manuscript (in revision). We also measured Al-Mg systematics by a combined approach of high-precision multiple-collector SIMS analyses, traditional analyses on the UCLA ims 1270, and high-spatial resolution analyses using a NanoSIMS instrument. The data help to deconvolve effects due to partial resetting of the Al-Mg system by multiple thermal events. Finally, we initiated investigations related to nebular heterogeneity with a new initiative of *in situ* high-precision sulfur isotope analyses of sulfides from a wide variety of components of chondrites. The ultimate goal of all this work is to help develop a better understanding of the relationships between CAIs and chondrules, the astrophysical environments in which they formed, and the timescales of nebular processes.

As detailed in Table 1, for the project period, 14 manuscripts were published and 17 abstracts were presented describing the work supported by NAG5-9789.

Table 1. Manuscripts supported by NAG 5-9789 during the project period 7/15/00 – 7/14/04

1. McKeegan K. D., Chaussidon M., and Robert F. (2000) Incorporation of short-lived ^{10}Be in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science* **289**, 1334-1337.
2. Russell S. S., MacPherson G. J., Leshin L. A., and McKeegan K. D (2000) ^{16}O enrichments in aluminum-rich chondrules from ordinary chondrites. *Earth and Planetary Science Letters* **184**, 57-74.
3. Guan Y., McKeegan K. D., and MacPherson G. J. (2000) Oxygen isotopes in calcium-aluminum-rich inclusions from enstatite chondrites: New evidence for a single CAI source in solar nebula. *Earth and Planetary Science Letters* **181**, 271-277.
4. Fagan T. J., McKeegan K. D., Krot A. N., and Keil K. (2001) Calcium-aluminum-rich inclusions in enstatite chondrites (II): Oxygen isotopes. *Meteoritics and Planetary Science* **36**, 223-230.
5. McKeegan K. D., Sahijpal S., Krot A. N., Weber D., and Ulyanov A. A. (2001) Oxygen isotopic compositions of Ca, Al-rich inclusions from CH chondrites: preservation of the primary oxygen isotopic reservoirs of the solar system. *Earth and Planetary Science Letters*, (revised version in review).
6. Simon S. B., Davis A. M., Grossman L., and McKeegan K. D. (2002) A hibonite-corundum inclusion from Murchison: a first-generation condensate from the solar nebula. *Meteoritics and Planetary Science* **37**, 533-548.
7. Krot A. N., McKeegan K. D., Russell S. S., Meibom A., Weisberg M. K., Zipfel J., Krot T. V., Fagan T. J., and Keil K. (2001) Refractory calcium-aluminum-rich inclusions and Al-diopside-rich chondrules in the metal-rich chondrites Hammadah al Hamra 237 and Queen Alexandra Range 94411. *Meteoritics and Planetary Science,* **36**, 1189-1216.
8. McKeegan K. D. and Leshin L. A. (2001) Stable isotope variations in extraterrestrial materials. In *Stable Isotope Geochemistry, Reviews in Mineralogy & Geochemistry* **43**, J. W. Valley and D. R. Cole (eds.), Mineralogical Society of America, Washington D.C., pp. 279-318.
9. Krot A. N., McKeegan K. D., Leshin L. A., MacPherson G. J., and Scott E. R. D. (2002) Existence of an ^{16}O-rich gaseous reservoir in the solar nebula. *Science* **295**(5557), 1051-1054.
10. McKeegan K. D. and Davis A. M. (2003) Early solar system chronology, pp. 431–460. In *Meteorites, Planets, and Comets* (Ed. A. M. Davis), Vol. 1 *Treatise on Geochemistry* (Eds. H. D. Holland and K. K. Turekian), Elsevier-Pergamon, Oxford.
11. Connolly H. C., Burnett D. S., and McKeegan K. D. (2003) The petrogenesis of type B1Ca-Al-rich inclusions: The spinel perspective. *Meteoritics and Planetary Science* **38**, 197-224.
12. Krot A. N., Fagan T. J., Keil K., McKeegan K. D., Sahijpal S., Hutcheon I. D., Petaev M. I., and Yurimoto H. (2004) Ca,Al-rich inclusions, amoeboid olivine aggregates, and Al-rich chondrules from the unique carbonaceous chondrite Acfer 094: I. Mineralogy and petrology. *Geochimica et Cosmochimica Acta* **68**, 2167-2184.
13. Kunihiro T., Rubin A. E., McKeegan K. D., and Wasson J. T. (2004) Initial $^{26}Al/^{27}Al$ in carbonaceous chondrite chondrules: Too little ^{26}Al to melt asteroids. *Geochimica et Cosmochimica Acta* **68**, 2947-2957.

Abstracts:

A1. Davis A. M., McKeegan K. D., and MacPherson G. J. (2000) Oxygen-isotopic compositions of individual minerals from the FUN inclusion Vigarano 1623-5. *Meteoritics & Planetary Science* **35**, A47-A47.

A2. Greenwood J. P., McKeegan K. D., and Wasson J. T. (2000) A Karoonda conundrum: Primordial oxygen in magnetite, olivine, and iron-rich spinel in a metamorphosed calcium-aluminium-rich inclusion. *Meteoritics & Planetary Science* **35**, A63-A64.

A3. Guan Y., McKeegan K. D., and MacPherson G. J. (2000) Oxygen-isotopic compositions in two calcium-aluminum-rich inclusions from unequilibrated ordinary chondrites. *Meteoritics & Planetary Science* **35**, A67-A67.

A4. McKeegan K. D., Chaussidon M. , Krot A. N. , Robert F. , Goswami J. N. , and Hutcheon I. D. (2001) Extinct radionuclide abundances in Ca, Al-rich inclusions from the CV chondrites Allende and Efremovka: A search for synchronicity. Lunar Planet. Sci. **XXXII**, #2175 (CDROM).

A5. Krot A. N. and McKeegan K. D. (2001) Oxygen-isotopic compositions of forsterite in an accretionary rim around a Ca,Al-rich inclusion and in an amoeboid olivine aggregate from the reduced CV chondrite Efremovka and their significance. Lunar Planet. Sci. **XXXII**, #2016 (CDROM).

A6. Krot A. N., McKeegan K. D., Russell S. S., Meibom A., Weisberg M. K., Zipfel J., and K. Keil (2001) ^{16}O-poor refractory inclusions in CB chondrites. Lunar Planet. Sci. **XXXII**, #1229 (CDROM).

A7. Chaussidon M., Robert F., McKeegan K. D., and Krot A. N. (2001) Lithium and boron isotopic compositions of refractory inclusions from primitive chondrites: a record of irradiation in the early solar system. Lunar Planet. Sci. **XXXII**, #1862 (CDROM).

A8. Goswami J. N., McKeegan K. D., Marhas K. K., Sinha N., and Davis A. M. (2001) Isotopic records in Murray and Murchison hibonites: Implications for the oxygen isotopic reservoirs in the early solar system. Lunar Planet. Sci. **XXXII**, #1576 (CDROM).

A9. McKeegan K. D., Krot A. N., Leshin L. A., and MacPherson G. J. (2001) Oxygen isotopic constraints on the origin and evolution of refractory components of chondritic meteorites. *Eleventh Annual Goldschmidt Conference* abstract #3848 (CDROM).

A10. Chaussidon M., Robert F., McKeegan K. D., and Krot A. N. (2001) Li, Be, B distribution and isotopic composition in refractory inclusions from primitive chondrites: a record of irradiation processes in the protosolar nebula. Meteoritics & Planetary Science **36**, A40.

A11. Krot A. N., McKeegan K. D., Meibom A., and Keil K. (2001) Oxygen-isotope compositions of condensate CAIs and chondrules in the metal-rich chondrites Hammadah al Hamra 237 and QUE 94411. Meteoritics & Planetary Science **36**, A106-A107.

A12. McKeegan K. D., Krot A. N., and Scott E. R. D. (2001) Variable oxygen isotopic compositions of gaseous reservoirs: clues to the formation of CAI and chondrules. Meteoritics & Planetary Science **36**, A129.

A13. Krot A. N., Aléon J., and McKeegan K. D. (2002) Mineralogy, petrography and oxygen-isotopic compositions of Ca, Al-rich inclusions and amoeboid olivine aggregates in the CR carbonaceous chondrites. Lunar Planet. Sci. **XXXIII**, #1412 (CDROM).

A14. Chaussidon M., Robert F., and McKeegan K. D. (2002) Incorporation of short-lived 7Be in one CAI from the Allende meteorite. Lunar Planet. Sci. **XXXIII**, #1563 (CDROM).

A15. Aléon J., Krot A. N., McKeegan K. D., MacPherson G. J., and Ulyanov A. A. (2002) Oxygen isotopic composition of fine-grained Ca-Al-rich inclusions in the reduced CV3 chondrite Efremovka. Lunar Planet. Sci. **XXXIII**, #1426 (CDROM).

A16. Aléon J., McKeegan K. D., Hutcheon I. D. and. Wasserburg G. J. (2002) Excesses of ^{36}S in sulfide-bearing Ca-Al-rich inclusions from Allende. Meteoritical Society meeting, in press.

A17. Greenwood J. P. and McKeegan K. D. (2002) Oxygen isotope composition of silica in ALH84001. Meteoritical Society meeting, in press.

Personnel supported by NAG 5-9789

At the beginning of the project period, postdoc Dr. Jerome Aléon was supported by NAG5-9789. He then left UCLA for a permanent research position with the CNRS in his native France. Dr. Marianna Cosarinsky (Ph.D. Arizona State University, 2004) replaced him as the postdoctoral researcher on this grant. an H1 visa). Additionally, Dr. Haibo Zou, UCLA research geochemist, worked part time with the PI on projects related to this grant. Dr. Zou is an expert in U-series isotope chemistry and clean-room techniques; he helped to develop novel applications for the ion probe and ICPMS laboratories. The research group also grew during the grant period by the addition of two new Ph.D. candidates, Dianne Taylor and Ming-Chang Liu. Both students are continuing under current NASA support.