Lunar & Planetary Surface Dynamics & Early History
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2004 Progress Report

Work supported during the current funding period of this grant has contributed to 13 publications and extended abstracts, (listed in the Appendix).

A. Early solar system processes and time scales using I-Xe chronometry: The I-Xe chronometer, based on the decay of 15.7 Ma ^{129}I, provides high-resolution records of post-formational meteorite evolution. Recent work has shown that the I-Xe system (Pravdivtseva, *et al.*, 1998; Brazzle, *et al.*, 1999; Gilmour, *et al.*, 2005) is concordant with the Mn-Cr ages of St. Marguerite and Richardton feldspar (Polnau and Lugmair, 2001), with the Hf-W chronometry reported by Quitté, *et al.* (2000) and with a large variety of Pb-Pb ages (Pravdivtseva, *et al.*, 2002a,b; Pravdivtseva, *et al.*, 2004a,b; Hohenberg, *et al.*, 2004a). In addition, the intercomparison of the absolute I-Xe ages of a large number of different samples with ages derived from other short-lived chronometers, and with high precision Pb-Pb ages (Gilmour, *et al.*, 2005) has provided the essential refinement of the absolute I-Xe age of the Shallowater reference sample. This has allowed the I-Xe chronometer become an integral part of the suite of radionuclear ages which shape our global understanding of the early evolution of solar system material. Moreover, since many iodine host minerals are secondary minerals, reliable absolute I-Xe ages have traced out in exquisite detail post-formational alteration history in the form of aqueous alteration in the carbonaceous chondrites (Krot, *et al.*, 2004; Gilmour, *et al.*, 2005) and progressive equilibration for the ordinary chondrites (Meshik, *et al.*, 2004b; Pravdivtseva, *et al.*, 2005a,b). I-Xe studies of different mineral phases of iron meteorites have provided a new approach to their cooling rates that are consistent with rates inferred by other means (Pravdivtseva, *et al.*, 1998; Hohenberg, *et al.*, 2004; Meshik, *et al.*, 2004c).

1) Refining the age of the I-Xe standard Shallowater (Absolute I-Xe ages): During our confirmation of the reliability the I-Xe system as a chronometer, relative I-Xe ages were directly compared with precision Pb-Pb ages in single mineral systems (Nichols *et al.* 1994; Brazzle, *et al.*, 1999; Hohenberg, *et al.*, 2000), the Pb-Pb age Acapulco phosphate, and its *relative* I-Xe age (relative to the Shallowater I-Xe enstatite standard), allowed the absolute age of Shallowater enstatite to be determined (Nichols *et al.* 1994). This provided the calibration necessary to convert relative I-Xe ages to absolute ages. Up until recently, this single datum was the basis for absolute I-Xe dating, and the Pb-Pb age of Acapulco phosphate had limited precision (± 2 Ma). Working in collaboration with Jamie Gilmour, Manchester, U.K., the entire suite of I-Xe ages was compared with those based upon other short-lived nuclides (Mn-Cr, Al-Mg) and with precision Pb-Pb ages on the same objects (Gilmour, *et al.*, 2005). This allowed a global re-normalization of the absolute I-Xe age of Shallowater enstatite to 4,563.2 ± 0.6 Gyr, a shift of 2.8 Ma from the previous value and, more importantly, a five-fold increase in precision. This time scale is of the order of that of aqueous alteration. It is, therefore, of essential importance in our understanding early solar system evolution by putting more precision into the specific times secondary alteration established by I-Xe.

2) Meteoritic magnetite and "Anomalous" I-Xe ages: The anomalously old I-Xe ages for Orgueil and Murchison magnetites reported by Lewis and Anders (1975) has long been an enigma, predating some of the oldest solar system condensates, Allende CAIs, by 10 Ma. Our recent work (Hohenberg, *et al.*, 2000; Gilmour, *et al.*, 2005) has conclusively demonstrated that these early results are in error, that these magnetites really formed 4.563 Ga ago, postdating Pb-Pb ages of the CAIs by several million yearts and the Shallowater reference standard by 2.8 ± 0.3 Ma. The probable mechanism of error was calibration failure of the KI irradiation monitor to correctly measure the neutron capture probability of iodine (Hohenberg, *et al.*, 2000; Gilmour, *et al.*, 2005). Moreover, all I-Xe ages determined using KI monitor, or those that use Murchison magnetite (MM) as the reference standard (which was calibrated using this KI monitor), are also in error, requiring a careful re-examination of many prior I-Xe results. It is far more difficult to obtain reliable I-Xe ages from direct measurement of neutron capture probability from iodine compounds for two major reasons. First, about 50% of the captures are due to sharp resonances in the epithermal region, establishing conditions for self-shielding in the high iodine concentration environment of pure compounds. Second, the high concentration of iodine in such compounds requires extreme dilutions which are technically difficult. Calibration of I-Xe ages by means of reference meteorites (Shallowater enstatite and Bjurböle have been used) with similar iodine concentrations (ppb range) are much more reliable. Results by other groups (cf. Holland, *et al.*, 2003) support these conclusions. Although not suitable as calibration monitors, magnetites in carbonaceous chondrites, being aqueous alteration products, carry important information about time of alteration on carbonaceous chondrites parent body. To compare onset of aqueous alteration in different types of carbonaceous chondrites we chemically separated magnetites from Orgueil (CI), Murchison (CM), Bali, Mokoia, Groznaia (CV), Lance, Colony, Kainzas (CO), Mac87300,64, Mac88107,51 (CR). These samples are going to be irradiated for I-Xe studies together with Orgueil and Murchison magnetites provided by R. Lewis.

3) Alteration history of the CV chondrites: Due to the fact that many iodine hosts are secondary phases, one of the unique properties of the I-Xe chronometer is its sensitivity to post-formational processes. The I-Xe isochron for sodalite, the major iodine carrier in Allende CAIs, indicates closure about 3 Ma after Pb-Pb closure in its refractory phases, constraining the time of aqueous alteration on the CV parent body, with individual I-Xe ages of 3.0, 3.1 and 3.7 Ma after Shallowater (± 0.2 Ma) for 3 Allende CAIs (Hohenberg, *et al.*, 1997; 1999; Pravdivtseva and Hohenberg, 2001; Krot, *et al.*, 2002; Pravdivtseva, *et al.*, 2002; Krot, *et al.*, 2004; Hohenberg, *et al.*, 2004). Allende dark inclusions, included in this study have individual I-Xe ages of -0.8 ±0.3, -1.1 ± 0.2, -1.5 ± 0.1 and -1.9 ± 0.2 before Shallowater (Krot, *et al.*, 2002; Pravdivtseva, *et al.*, 2002a,b; Hohenberg, *et al.*, 2004a, Krot, *et al.*, 2004). This seems to indicate two different stages of aqueous alteration, an early alteration stage, predating Shallowater by ~ 1 Ma, and a later stage terminating (lasting?) ~ 3 Ma after Shallowater. The I-Xe system of Allende dark inclusions were largely not reset by most recent alteration, but the fine-grained CAIs largely were (Pravdivtseva, *et al.*, 2002b,c; Pravdivtseva, *et al.*, 2003a,b; Krot, *et al.*, 2004).

4) I-Xe dating and cooling rates of iron meteorites: Using laser extraction from single silicate inclusions from Colomera, we determined feldspar to be the major iodine carrier of these silicates. A composite feldspar sample of 12 individual mineral grains was irradiated yielding an absolute I-Xe isochron age of 4556 ± 2 Ma (Pravdivtseva, *et al*, 2001). Model I-Xe ages of individual temperature fractions of the Colomera feldspar approach the linear isochron age in the systematic manner of progressive closure. From cooling theory (Dodson, 1973), our Colomera data yield a cooling rate of 2 to 4°C/Ma, and closure temperature ~ 450°C (Pravdivtseva, *et al.*, 2000; Pravdivtseva, *et al.*, 2001; Hohenberg, *et al.*, 2004b). Polished section of iron Campo del Cielo was investigated for phases that carry radiogenic ^{129}Xe using our *insitu* laser extraction technique with positive results for eight individual silicate inclusions (Meshik, *et al.*, 2004c). All diopside and albite crystals were extremely enriched in radiogenic ^{129}Xe (compared to normal trapped Xe), while metal-rich phases have no measurable ^{129*}Xe. Physical separation of ^{129*}Xe–reach phases is under way, the neutron irradiation to determine I-Xe ages of these individual phases will follow.

B. I-Xe studies of individual chondrules. Comparisons of I-Xe ages and high-precision Pb-Pb ages in individual chondrules are being done in collaboration with Yu Amelin. Although originally this work was undertaken to locate the specific iodine carriers in chondrules and to evaluate whether the I-Xe and Pb-Pb chronometers should expected to be concordant, it has been far more fruitful than simple comparisons of the two chronometers. In fact, comparison of I-Xe and Pb-Pb ages from Richardton chondrules and separated mineral phases first suggested that absolute age normalization is 2.8 Ma too old. Recent analysis of 4 Elenovka chondrules (Pravdivtseva, *et al.* 2004b) strongly supports this observation. New normalization places I-Xe ages for chondrules in low metamorphic grade ordinary chondrites tightly within a few Ma of the Pb-Pb ages of CAIs (Pravdivtseva, *et al.* 2004a). In addition, comparison of I-Xe and Pb-Pb ages of Elenovka chondrules showed that I-Xe system is more retentive under slow cooling conditions, characteristic of Elenovka. New data for unnamed Antarctic meteorite LL3.6 (Pravdivtseva *et al.* 2005, Pravdivtseva *et al.* 2004a, Meshik, *et al.* 2004b;) together with previous data by other authors for LL3 meteorites demonstrated correlation between I-Xe ages and metamorphic grades of LL3 meteorites, reflecting post-formational metamorphism (Pravdivtseva, *et al.* 2005).

C. Additional Ongoing Projects:

1) Chemically Fractionated Fission Xenon (CFF-Xe) and Natural Reactors (Oklo): As a continuation of our initial study of Zone 13 Oklo reactor (Meshik, *et al.* 2000), we have conducted an intensive study of the operational properties of this reactor through detailed analyses of laser-extracted Xe from different minerals. Combinations of isotopic results from uranium-rich minerals and uranium-poor minerals of this reactor, and Xe studies of other fission phenomena (Meshik, *et al.* 2004b) has led to an exquisite understanding of this natural reactor (Meshik, *et al.* 2004a).

2) Double beta-decay: a) We previously reported the absolute ββ-decay rates for ^{128}Te and ^{130}Te, the longest half-lives ever measured experimentally. One potential problem in these old samples is the possibility of Xe loss from native Te, a low-melting point mineral. This, in fact, is reflected in the ββ-decay half-lives reported by different groups, which tend to cluster in two groups that differ in apparent ^{130}Te half-life by a factor of 2 (^{128}Te is another story since our group is the only one apparently able to measure its exceedingly long half-life). To address this, we irradiated four tellurium samples (producing ^{131}Xe from ^{130}Te n-capture) used in our own work. For all four samples, > 95% of the newly produced ^{131}Xe correlates with the ββ ^{130}Xe, implying quantitative retention and confirmation of our earlier results. Therefore, the only remaining cause must be the assumption that the Xe retention time is accurately provided by the Pb-Pb age of the host formation in which the native Te is found. For several years we have been performing a series of experiments on Xe diffusion in native tellurium. We have shown by careful laboratory experiments involving vacuum heating which lasted several years that the Te–Xe system can be reset by relatively mild heating. This can occur during modest hydrothermal events (400-500°C) that are known to have occurred in some of these deposits. These do not seem to affect Pb-Pb system, but they do lead to variable amounts of Xe loss, which explains the variable results for the apparent ββ-decay lifetime of ^{130}Xe, with the shortest half-life cluster the more accurate. These experiments were completed during 2004 and manuscript on the results is in preparation.

3) Development of the next generation of noble gas mass spectrometers: As members of the Genesis Science Team, we are committed to the task of improving our analytical capabilities for the measurement of the returned solar wind samples. Noble gases are probably the elements least prone to contamination and, with the failure of parachute to deploy, precise noble gas results represent an increasingly important part of the Genesis measurements. While the hexagonal collector substrates are degraded, the polished aluminum "kidney" (radiation shield for the batteries) is bent but largely intact and has been divided for initial studies (Allton, *et al.* 2004). Our current instruments have very low blanks and operate in ion-counting modes, so we already have optimum sensitivity for these measurements, but we cannot measure but one isotope at a time. The only way to improve our capabilities is to develop noble gas instruments with multiple electron multipliers. We have built, and are in the process of refining, a multiple multiplier version of our current instrument. In addition, we have received funding to develop an entirely new instrument in collaboration with Nu-Instruments, Manchester, U.K. This instrument has arrived and we are in the process of expanding its capabilities, by reducing its electronic noise and refining its data analysis software. Both of these new instruments will contribute to our Cosmochemistry program by greatly expanding our analytical capabilities in sensitivity and precision.

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Publications during 2004

Papers:

1. J. D. Gilmour, O. V. Pravdivtseva, A. Busfield and C. M. Hohenberg. (2005) The I-Xe Chronometer and the Early Solar System. *Meteoritics and Planetary Science* (submitted)
2. A. N. Krot, I. D. Hutcheon, A. J. Brearly, O. V. Pravdivtseva, M. I. Petaev and C. M. Hohenberg (2004) Timescales and Settings for Alteration of Chondritic meteorites. *Meteorites and the Early Solar System II* (submitted).
3. C. M. Hohenberg, O. V. Pravdivtseva, A. P. Meshik. (2004a) Trapped Xe and I-Xe ages in aqueously altered CV3 meteorites. *Geochim. Cosmochim. Acta* 68, 22, pp.4745-4763.
4. A. P. Meshik, C. M. Hohenberg, O. V. Pravdivtseva. (2004a) Record of cycling operation of the natural nuclear reactor in the Oklo/Okelobondo area in Gabon. *Physical Review Letters* 93, 18, 182302-1 – 182302-4.

Abstracts:

5. O. V. Pravdivtseva, C. M. Hohenberg, and A. P. Meshik. (2005) I-Xe Dating: The time line of chondrule formation and metamorphism in LL chondrites. *Lunar Planet. Sci. XXXVI,* Abstract 2354.
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12. A. P. Meshik, G. Kurat, O. V. Pravdivtseva and C. M. Hohenberg. (2004d) Radiogenic 129-xenon in silicate inclusions in the Campo del Cielo iron. *Lunar Planet. Sci. XXXV,* Abstract 1687.

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