Solar composition from the Genesis Discovery Mission

D. S. Burnett[1] and Genesis Science Team[2]

Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

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Science results from the Genesis Mission illustrate the major advantages of sample return missions. (*i*) Important results not otherwise obtainable except by analysis in terrestrial laboratories: the isotopic compositions of O, N, and noble gases differ in the Sun from other inner solar system objects. The N isotopic composition is the same as that of Jupiter. Genesis has resolved discrepancies in the noble gas data from solar wind implanted in lunar soils. (*ii*) The most advanced analytical instruments have been applied to Genesis samples, including some developed specifically for the mission. (*iii*) The N isotope result has been replicated with four different instruments.

solar oxygen isotopes | solar nitrogen isotopes | solar noble gases | solar abundances

The Sun has obvious importance to the understanding of the physics of the solar system, but it is of equal major importance to the composition of planetary materials, i.e., the research area known as cosmochemistry. The link between solar and planetary matter is that they have a common origin in the original cloud of gas and dust from which the solar system formed 4.57×10^9 years ago. Our gas-dust cloud is the first step in what cosmochemists regard, at least implicitly, as a "Standard Model" for the origin of planetary materials. The formation of the Sun by gravitational collapse of the cloud occurs by the flow of material through an equatorial disk, the "solar nebula," onto the Sun, a process now directly observable in star-forming regions. The Standard Model regards elemental (the relative amounts of different elements) and isotopic (the relative amounts of the isotopes of individual elements) compositions of the solar nebula as homogeneous, at least on large scales relative to the size of individual dust grains. The planetary objects (planets, moons, asteroids, etc.) of the solar system are notable for their amazing degree of diversity yet they appear to have formed from a homogenous starting point. Most of the material in the solar nebula flowed to the Sun, thus in the solar surface layers, isolated from nuclear transformations in the solar core, the original average nebular composition is preserved for the vast majority of elements and isotopes. The Standard Model appears to be sufficiently accurate to serve as a starting point; it obviously leaves a lot to be desired in terms of specificity, and most interestingly, it is clearly wrong in terms of the variations in the isotopic composition of some elements. For example, at the level of a few percent or less, there are variations in the isotopic composition of O among inner solar system materials available for laboratory study (1).

Knowledge of the elemental composition of solar matter is available from the photospheric absorption line spectrum, although there has been recent controversy over accuracy. High precision isotopic data on solar matter was totally lacking prior to the NASA Genesis Discovery Mission. The major science objective of Genesis was thus (*i*) to obtain isotopic compositions for solar matter to the level of precision required for planetary science purposes. Such precision required a sample return mission. Fortunately, there is a readily obtainable source of solar matter continuously flowing past the Earth in the form of the solar wind. The remaining Genesis general science objectives are: (*ii*) make a significant improvement in the knowledge of solar elemental abundances; (*iii*) obtain independent compositional data for the three different types of solar wind (2); and (*iv*) leave behind a reservoir of solar matter for more advanced studies. Objective (*iv*) is an important characteristic of all sample return missions.

Genesis placed a spacecraft at the easily reached L1 Lagrangian point, approximately 1% of the distance to the Sun, but away from perturbing influences of the terrestrial magnetic field. The solar wind is a highly-ionized, radially-outward-flowing plasma with a velocity corresponding to about 450 km/sec for individual ions. At these velocities the solar wind ions are retained when they strike materials. Ultrapure materials were exposed to the solar wind at L1 for 27 mo, and then returned to Earth for analyses in terrestrial laboratories. The Genesis Project hit bottom (literally) on September 8, 2004 when the parachute deployment failed and the sample return capsule crashed. We went out and picked up the pieces (literally) of our collector materials and started the long road back to attempting to accomplish our long list of measurement objectives. This paper is a brief summary of how far we've come.

Genesis as an Example of a Sample Return Mission

In the following, I will use Genesis results to illustrate the advantages of sample return missions: (*i*) High science return. Planetary materials contain a record of conditions, processes, and events accompanying their formation that can be read given the opportunity for detailed study in terrestrial laboratories. Unlike meteorites, materials from a sample return mission have a well documented solar system origin. (*ii*) No limitations on the analytical instruments used. (*iii*) Important results can be verified by replicate analysis, ideally using different techniques and/or samples. Item (*iii*), essentially the use of the scientific method, is impossible for practical reasons for nonsample-return missions. (*iv*) Curated samples available when new instruments are developed. (*v*) Significant participation by large numbers of scientists. In the case of Genesis, the selection and analysis of collector materials has involved serious efforts from 32 laboratories around the world.

Collector materials are of two types (Fig. 1): 10 cm hexagons mounted in arrays (Fig. 1 *A* and *B*) and 3 cm radius circular quadrants ("targets") mounted in the center of a focusing ion telescope ["concentrator" (3); Fig. 1*C*]. Most Genesis instruments count solar wind atoms one at a time, thus the appropriate unit for the amount of solar matter returned is atoms. Genesis science is focused on the 0.1% of the elements beyond H and He. Here,

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[1]To whom correspondence should be addressed. E-mail: burnett@gps.caltech.edu.

[2]A complete list of the members of the Genesis Science Team is available in the supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1014877108/-/DCSupplemental.

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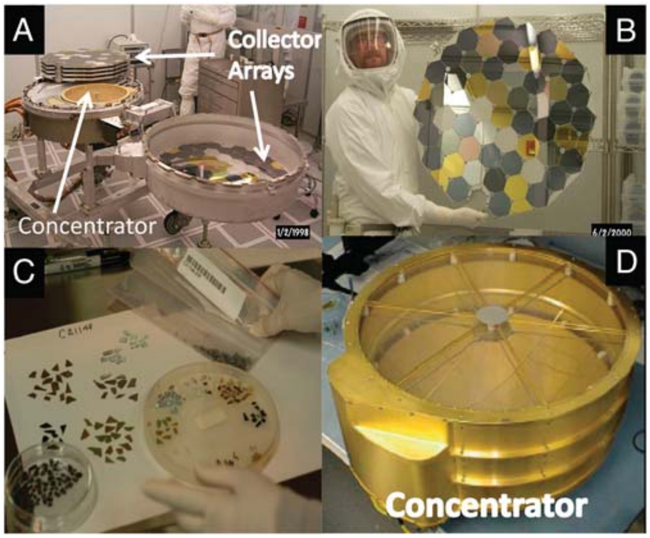

Fig. 1. Overview of Genesis collector materials. (*A*) Canister as opened at L1. Materials were 10 cm hexagons mounted in five arrays as shown in (*B*). One of the lower three arrays in stack was exposed to the solar wind to separately sample solar wind regimes. Reentry crash broke hexagons, but pieces down to 3 mm size were sorted (*C*). (*D*) Concentrator: a focusing ion telescope designed to give ×20 enhanced signal to noise for O and N isotopic measurements (2).

4×10^{17} atoms were collected on the arrays. The crash caused serious losses; fractions lost vary with material. Assuming that the smallest useful sample is 3 mm in size (Fig. 1*C*), losses range from roughly 50% (sapphire) to >99% (Ge).

Illustrating Advantage *ii* above, a wide variety of advanced analytical instruments have been used (Fig. 2). Genesis sample analysis required a new generation of analytical instruments. Shown are the MegaSIMS (high energy ion probe) at UCLA (Fig. 2*A*) (4) and SARISA, a resonance ionization mass spectrometer at Argonne National Laboratory (ANL) (Fig. 2*B*) (5). Typically, there are two steps in Genesis sample analyses. First, the solar wind atoms are extracted from the collector materials, and then the atoms are counted, in most cases by the use of a mass spectrometer. Fig. 2*C* shows pits in a mm-size Si fragment made by UV laser ablation (6). He and Ne were released during the ablation, ionized with an electron beam, then the ions analyzed with a noble gas mass spectrometer. Genesis has also exploited the capabilities of modern synchrotron radiation facilities (e.g., the Advanced Photon Source at the Argonne National Lab; Fig. 2*D*) using Total Reflection X-ray Fluorescence (7).

Fig. 2. (*A*) The MegaSIMs, an accelerator and secondary ion mass spectrometer hybrid at UCLA (4). The instrument fills a whole room and weighs more than the Genesis spacecraft. McKeegan research group for scale. (*B*) SARISA, a laser resonance ionization mass spectrometer at ANL (5). Emil Tripa and Igor Veryovkin for scale. (*A*) and (*B*) were developed specifically for Genesis. (*C*) Pits in a mm-sized Genesis Si sample made by rastering a UV laser, releasing He and Ne to be analyzed by noble gas mass spectrometry at the Eidgenösssische Technische Hochschule, Zurich (6). (*D*) Some instruments used for Genesis sample analysis are larger than NASA centers. Here the Advanced Photon Source at ANL (7). Small dots at bottom of image are automobiles.

Science Results

The crash has slowed our work considerably; nevertheless, the following summary covers only a fraction of the available results from Genesis sample analyses.

O Isotope Analyses. Fig. 3 shows schematically the variations in O isotopic compositions among inner solar system materials (8). The Genesis solar wind composition, measured with the UCLA MegaSIMS (Fig. 1*A*), is very different from most inner solar system materials, but lies near the linear trend set by meteoritic Ca-Al-rich inclusions (CAI). Models of solar wind acceleration (9) predict that O isotopes in the solar wind will be richer in ^{16}O than the Sun, with the amount of correction shown by the dashed line in Fig. 3. It is possible that the amount of correction shown is too large, so within present errors, the solar composition could lie on the CAI line. Several well studied natural processes exist which fractionate isotopes relative to the assumed Standard Model values, but none of these explain the variations shown on Fig. 3. A specific model based on the effects of self-shielding of ultraviolet radiation from the early Sun (10) predicts that the solar O isotopic composition would be ^{16}O-rich, lying along the CAI trend. The details of how this process would affect *all* of the material in the inner solar system are not clear. Conceivably, UV radiation plays a role in the growth of grains from micron to kilometer size. The Genesis $^{18}O/^{16}O$ ratio is lower by 17% from the ratio derived from intensities of solar molecular CO lines (11). It appears unlikely that Sun-solar wind isotopic frac-

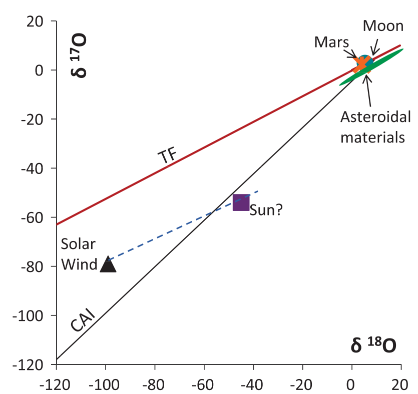

Fig. 3. A mass spectrometer measures separately the ion currents for the different isotopes of an element. Oxygen has three isotopes, allowing two isotopic abundance ratios to be calculated. Intersample variations are calculated as the fractional deviation δ of the measured $^{18}O/^{16}O$ or $^{17}O/^{16}O$ from terrestrial ocean water (‰ units are permil, parts in 1,000). Terrestrial geochemical processes produce a wide range in O isotope fractionations, but these variations lie almost entirely on the line labeled TF (terrestrial fractionation). The Genesis solar wind composition (8) is very different from the major inner solar system objects (Earth, Moon, Mars) and most asteroidal (meteoritic) materials, but lies close to the trend set by unique high temperature Ca-Al-rich inclusions (CAI). Theoretically, solar wind acceleration fractionates isotopes by the amount shown by the line between the solar wind and the Sun? point (9).

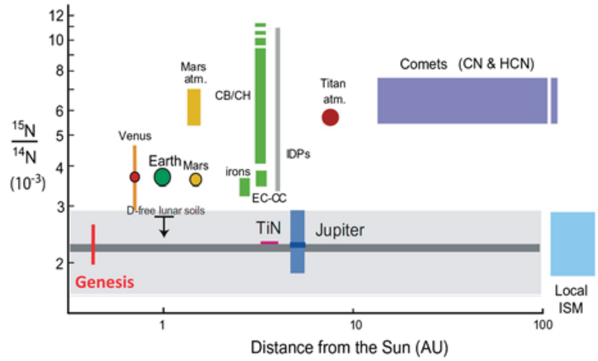

Fig. 4. N isotopic compositions in solar system objects, [modified from Marty et al., (13)] vary widely, showing no simple heliocentric distance trend. Genesis data (13–16) show that the Sun is like Jupiter, whereas all inner solar system samples show much larger amounts of ^{15}N. The TiN analysis refers to a mineral from an unusual meteorite (17). The origins of these variations are unknown.

tionation of this magnitude has occurred; the origin of the discrepancy is unknown.

N Isotope Analyses. The variations in $^{15}N/^{14}N$ among solar system materials are much larger than for O and cannot be explained by well studied mechanisms of isotope fractionation. Although one analysis has given a higher ratio for as-yet-unknown reasons (12), Genesis data overall (13–17) show that the Sun is like Jupiter and very distinct from any known inner solar system material (Fig. 4). In this case four independent replicate analyses using different instruments was able clearly to recognize an anomalous result, illustrating the major advantage of sample return missions (Advantage *iii* above). No good models exist to explain the large solar system N isotopic variations.

Noble Gas Isotopic Compositions. The inspiration for Genesis was the Apollo Solar Wind Composition (SWC) foil experiments (18) which showed that the $^{20}Ne/^{22}Ne$ ratio in the terrestrial atmosphere was 38% lower than that in the solar wind. Genesis has confirmed this important result with higher precision (6, 19), and more importantly, extended the documentation of differences between the solar wind and terrestrial atmosphere to the other noble gases. Fig. 5 compares the Genesis $^{36}Ar/^{38}Ar$ (6, 19) with (*i*) previous solar wind estimates from the Apollo SWC (18), (*ii*) measurements of solar wind implanted in lunar regolith samples (20, 21), and (*iii*) the in situ instrument on the Soho spacecraft (22). The Genesis data indicate a solar wind—atmospheric Ar isotopic fractionation of $2.5 \pm 0.1\%$ in the same sense as Ne. The precise Ne and Ar solar wind- atmo-

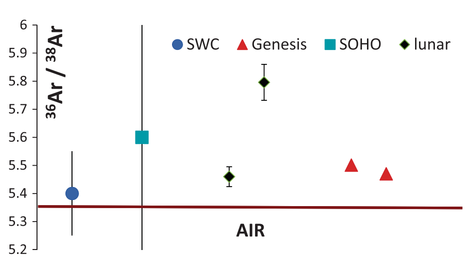

Fig. 5. Comparison of various data for solar wind Ar isotopic composition compared to that of terrestrial atmosphere (air). The Genesis data (6, 19) have error bars smaller than the symbol size and provide a precise measure of the Ar fractionation of the terrestrial atmosphere that could not be obtained from Apollo SWC data. The necessity of sample return to measure relatively small but important differences is illustrated by comparison with the Soho spacecraft instrument analysis (22). The Genesis results match the lunar regolith value of ref. 20 but not ref. 21.

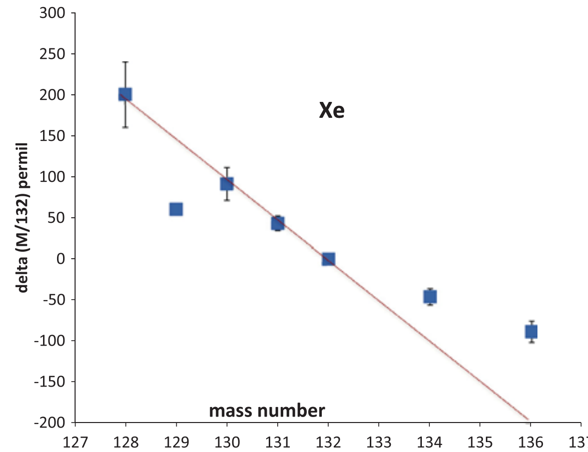

Fig. 6. Permil deviations of Genesis solar wind Xe relative to the terrestrial atmosphere (24) have a more complex fractionation pattern than the other noble gases. Relative to an assumed mass fractionation trend from masses 128 through 131, the ^{129}Xe anomaly reflects contributions from the decay of ^{129}I to initial terrestrial materials. The deviations at 134 and 136 are less clear (23). These deviations were recognized from the first measurements of solar wind in Apollo lunar soil samples. Genesis and lunar data agree well.

sphere isotopic differences will permit improved models of fractionation caused by an episode of early atmospheric loss of the atmosphere [e.g., (23)]. Comparison of the Genesis and Soho data (Fig. 3) illustrates the necessity of sample return missions to address cosmochemical isotope problems.

Xe Isotopic Composition. Fig. 6 shows the permil (parts in 1,000) deviation of the Genesis solar wind $^{M}Xe/^{132}Xe$ relative to the terrestrial atmosphere (24). The pattern is one of an overall increasing depletion of the atmosphere in the lighter isotopes, in the same qualitative sense as for Ne and Ar. The Genesis data agree with those derived previously from solar wind implanted in lunar soils in showing that solar wind and atmospheric Xe are not related by a simple mass fractionation relation as assumed for Ne and Ar; however, it is widely accepted that the deviations from a linear trend on Fig. 6 at mass 129 are caused by additions to the atmosphere from the radioactive decay of ^{129}I. The deviations at masses 134 and 136 are less clear (23). The linear portion of Fig. 6 from masses 128 through 131 would correspond to a trend of roughly 4%/amu which is actually higher than inferred from $^{36}Ar/^{38}Ar$; whereas mass dependent fractionation should be smaller for heavier elements. This difference between light and heavy elements is a major challenge for models ascribing the solar wind—atmosphere difference to atmospheric mass loss. Precise Kr isotopic data are available from Genesis samples (25) that show the same light isotope enrichment trends; final calibrations of the amount of mass fractionation are in progress.

Solar Wind—Sun Isotopic Fractionation. The three different types ["regimes" (2)] of solar wind [High speed, Low speed, and Coronal Mass Ejection (CME)] were successfully collected by Genesis. A major application of the regime collections was to provide data to test the possibility of isotope fractionation between the Sun and the solar wind. Large short-term variations in $^{3}He/^{4}He$ are known from spacecraft instruments (26), but based on the Apollo SWC data (18) it appears that long term (few days?) averages converge to a well defined solar wind $^{3}He/^{4}He$. Beyond He, the extent of solar wind isotope fractionation was unknown. Genesis data from Heber et al. (27) (Fig. 7) have provided precise data of interregime isotopic variations with the largest differences, between IS and CH, of 6.3, 0.8, and 0.3% for He, Ne, and Ar. The differences in Fig. 7 are not especially large, but the concern is that these might be small residual dif-

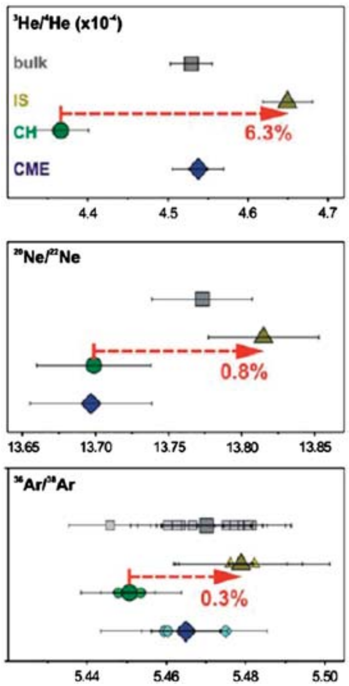

Fig. 7. Relative to bulk solar wind collectors, the Low speed (IS), High speed (CH), and Coronal Mass Ejection (CME) regime samples show precisely defined differences in the He, Ne, and Ar isotopic compositions (27).

ferences from large fractionations between the Sun and all kinds of solar wind. Measurements of Mg isotopic compositions on Genesis samples, now in progress (28), will provide significant constraints.

Conclusions

In the original Genesis Mission planning, we identified 19 specific prioritized measurement objectives. Progress on a selected set of these is reported here. Many other examples could be discussed. The Sample Return Capsule crash has made meeting these objectives much more difficult both in terms of loss of collector materials and because of particulate surface contamination. The latter has thus far prevented analyses of large areas, required to meet some of the objectives, but major efforts at particulate removal are underway. We have not given up on any of our original objectives. The reason for optimism is illustrated in Fig. 8 which shows that the solar wind is cleanly separated from the crash derived particulate contamination, although the amount of separation is small in absolute terms. The contamination is *on* the surface; the solar wind is *below* the surface; moreover, being a sample return mission, all of contemporary science and technology is available to aid with the cleaning. Based on present trends the only effect of the crash will be delays in meeting Genesis science objectives.

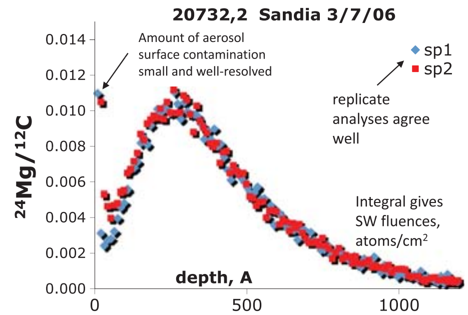

Fig. 8. Depth profile of solar wind Mg. A SIMS depth profile (Jurewicz, Guan, ASU) measures the ion counting ratio Mg/C from a diamond-like-C collector as a function of depth. Crash-derived surface contamination is cleanly separated from the implanted solar wind.

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Supporting Information

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Genesis Science Team

Allton, J. H., Johnson Space Center, Houston, TX 77058 USA

Barraclough, B. L., Los Alamos National Laboratory, Los Alamos, NM 87545

Baryshev S.V., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439

Baur, H., Eidgenösssische Technische Hochschule Zurich, Earth Sciences, CH-8092 Zurich, Switzerland

Bixler, A., Space Sciences Laboratory University of California Berkeley, CA 94720-7450

Buehler, F., University of Bern, Physikalisches Institut, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

Butterworth, A.L., Space Sciences Laboratory, University of California Berkeley, CA 94720-7450

Becker, R. H., School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

Bochsler, P., University of Bern, Physikalisches Institut, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

Brennan, S., Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Stanford, CA 94025

Burkett, P. J., Johnson Space Center, Houston, TX 77058.

Burnard, P.G., Centre de Recherches Pétrographique et Géochemiques, Centre National de la Recherche Scientifique, Université de Nancy, BP20, 54501 Vandoeuvre Cedex, France

Caffee, M.W., Department of Physics, Purdue University, West Lafayette, IN 47906

Calaway, M. J., Johnson Space Center, Houston, TX 77058.

Calaway, W.F., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.

Campbell, A. J., Department of the Geophysical Sciences The University of Chicago, Chicago, IL 60637.

Cetina, C., Naval Research Laboratory, Washington, DC 20375.

Chakraborty, S., Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California 92093-035

Chaussidon, M., Centre de Recherches Pétrographique et Géochemiques, Centre National de la Recherche Scientifique, Université de Nancy, BP20, 54501 Vandoeuvre Cedex, France

Crowther, S.A., School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom.

Clark, B., Lockheed Martin Denver, CO, 80201

Coath, C. D., Dept. of Earth Sciences, Univ. of Bristol, Bristol, BS8 1RJ, United Kingdom

Choi, Y., Consortium for Advanced Radiation Sources and Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637.

Cyr, Kimberly, Johnson Space Center, Houston, TX 77058 USA

Dominguez, Gerardo, University of California, San Diego, La Jolla, CA 92093-035

Eberhardt, P., University of Bern, Physikalisches Institut, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

Ebihara, M., Department of Chemistry, Graduate School of Science and Engineering, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-03, Japan.

Eng, P. J., Consortium for Advanced Radiation Sources and Department of Geophysical Sciences University of Chicago, Chicago, IL 60637.

Farquhar, J., Earth System Science Interdisciplinary Center and Department of Geology, University of Maryland, College Park, MD 20742.

Franchi, I. A., Research Institute, Open University, Walton Hall, Milton Keynes MK7 6AA, Bucks, United Kingdom

Friedman, T. F., Sandia National Laboratories, Albuquerque, NM 87185.

Gainsforth Z., Space Sciences Laboratory University of California Berkeley, CA 94720-7450.

Ghose, S. K., Consortium for Advanced Radiation Sources and Department of Geophysical Sciences University of Chicago, Chicago, IL 60637.

Gilmour, J.D., School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom.

Grabowski, K. S., Naval Research Laboratory, Washington, DC 20375.

Grimberg, A., Max Planck Society, Administrative Headquarters, Hofgartenstrasse 8, D-80539 Munich, Germany.

Guan, Y., Geo. Planetary Sci., CalTech Pasadena, CA 91125.

Heber, V.S., Dept. of Earth and Space Sciences, UCLA, Los Angeles, CA 90095-1567.

Hervig, R. V., Arizona State University, Center for Meteorite Studies and School of Earth and Space Exploration, Tempe, AZ 85287-1404.

Huang, S., Dept. of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02189.

Hull, J., Space Sciences Laboratory, University of California Berkeley, CA 94720-7450

Jarzebinski, G., Dept. of Earth and Space Sciences, UCLA, Los Angeles, CA 90095-1567.

Jurewicz, A.J.G., Arizona State U CMS/SESE, Tempe, AZ 85287-1404.

Henkel, T., The University of Manchester, Manchester, M13 9PL, United Kingdom.

Hohenberg, C.M., Washington University, St. Louis, MO 63130.

Humayun, M., National High Magnetic Field Laboratory and Dept. of the Geological Sciences, Florida State University, Tallahassee, FL 32310.

Huss, G. R., Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, HI 96822.

Kallio, A.P., Dept. of Earth and Space Sciences, UCLA, Los Angeles, CA 90095-1567.

King, B. V., School of Physical and Mathematical Sciences, University of Newcastle, Callaghan 2308, Australia.

Kitts, K., Department of Geology and Environ. Geosciences, Northern Illinois University, DeKalb, IL 60115.

Kuhlman, K.R., Planetary Science Institute, 1700 East Fort Lowell Blvd., Suite 106, Tucson, AZ 85719.

Kunihiro, T., Okayama Univ., Misasa, Tottori 682-0193 Japan.

Lyon, I., The University of Manchester, Manchester, M13 9PL, United Kingdom.

Mabry, J. C., Washington University, St. Louis, MO 63130.

Mao, P.H., Physics, Mathematics, and Astronomy, Caltech, Pasadena, CA 91125.

Marrocchi, Y., Washington University, St. Louis, MO 63130.

Marty, B., Centre de Recherches Pétrographique et Géochemiques, Centre National de la Recherche Scientifique, Université de Nancy, BP20, 54501 Vandoeuvre Cedex, France.

McKeegan, K. D., Dept. of Earth and Space Sciences, UCLA, Los Angeles, CA 90095-1567.

McNamara, K. M., Johnson Space Center, Houston, TX 77058.

Meshik, A. P., Washington University, St. Louis, MO 63130.

Moses, R., Space Sciences and Applications Los Alamos National Laboratory, Los Alamos, NM 87544.

Nagashima, Kazuhide, University of Hawai'i at Manoa, Honolulu, HI 96822

Neugebauer, N., U. of Arizona, Tuscon, AZ

Ngo, H., Jet Propulsion Laboratory, Pasadena, CA 91109.

Nishiizumi, K., Space Sciences Laboratory University of California Berkeley, CA 94720-7450.

Nittler, L., Dept. of Terrestrial Magnetism, Carnegie Institution, Washington, DC 20015-1305.

Nordholdt J.E., Space Sciences and Applications Los Alamos National Laboratory, Los Alamos, NM 87544.

Olinger, C., Applied Modern Physics, Los Alamos National Laboratory, MS D410, Los Alamos, NM 87544.

Palma, R. L., Department of Physics and Astronomy Minnesota State University, Mankato, MN 55317

Papanastassiou, D. A., Jet Propulsion Laboratory, Pasadena CA 91109.

Paque, J. M., Geo. and Planetary Sciences, CalTech, Pasadena CA 91125.

Pepin, R. O., School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

Pellin, M. J., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.

Pianetta, P., Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Stanford, CA 94025.

Pravditseva, O. V., Washington University, St. Louis, MO 63130.

Reisenfeld, D.B., Dept. of Physics and Astronomy, U. Montana (Missoula, MT).

Rieck, K., Arizona State U, Tempe, AZ 85287-1404.

Rodriguez, M. C., Johnson Space Center, Houston, TX 77058.

Sasaki, C. N., Jet Propulsion Laboratory, Pasadena, CA 91109.

Sestak, S., Commonwealth Scientific and Industrial Research Organisation, Earth Science and Resource Engineering, PO Box 136, North Ryde, NSW 1670, Australia.

Schlutter, D. J., School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

Schmeling, M., Chemistry Department, Loyola University, Chicago, IL 60626.

Smith, S., Evans Analytical Group, 810 Kifer Road Sunnyvale, CA 94086-520.

Srnivasan G., Department of Geology, University of Toronto. Toronto M5S 3B1, Canada.

Stansbery, E.K., NASA, Johnson Space Center, Houston, TX 77058.

Steinberg, J., Space Sciences and Applications Los Alamos National Laboratory, Los Alamos, NM 87544.

Sutton, S. R., Consortium for Advanced Radiation Sources and Department of Geophysical Sciences University of Chicago, Chicago, IL 60637.

Sweetnam, D. N., Jet Propulsion Laboratory, Pasadena, CA 91109.

Tripa, C. E., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.

Thiemens, M. H., Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, CA 92093-0356.

Tokar, R., Space Sciences and Applications Los Alamos National Laboratory, Los Alamos, NM 87544.

Verchovsky, A. B., Planetary and Space Sciences Research Institute, Open University, Walton Hall, Milton Keynes MK7 6AA, Bucks, United Kingdom.

Veryovkin, I. V., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.

Vogel, N., ETH Zurich, Earth Sciences, CH-8092 Zurich, Switzerland.

Wadhwa, M., Arizona State U Tempe, AZ 85287-1404.

Wang, J., Dept. of Terrestrial Magnetism, Carnegie Institution, Washington, DC 20015-1305.

Welten, K,C., Space Sciences Laboratory, University of California Berkeley, CA 94720-7450

Westphal, A. J., Space Sciences Laboratory, University of California Berkeley, CA 94720-7450.

Wieler, R., Eidgenösssische Technische Hochschule, Zurich, Earth Sciences, CH-8092 Zurich, Switzerland.

Wiens, R. C., Space Sciences and Applications Los Alamos National Laboratory, Los Alamos, NM 87544.

Woolum, D.S., Dept of Physics, Cal State Fullerton, Fullerton, CA 92634.

Zimmerman. L., Centre de Recherches Pétrographique et Géochemiques, Centre National de la Recherche Scientifique, Université de Nancy, BP20, 54501 Vandoeuvre Cedex, France.

Zinovev, A. V., Materials Science Division, Argonne National Laboratory, Argonne, IL 60439.