

Solar composition from the Genesis Discovery Mission

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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 ele-

mental 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. 1A and B) and 3 cm radius circular quadrants (“targets”) mounted in the center of a focusing ion telescope [“concentrator” (3); Fig. 1C]. 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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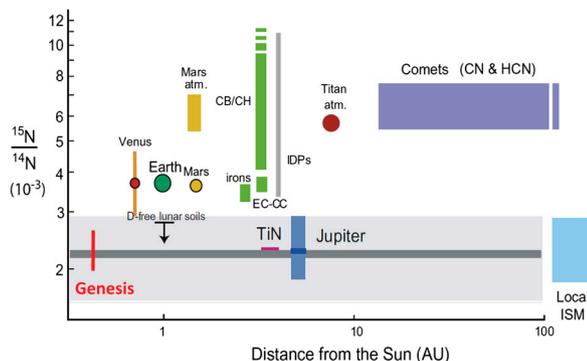


Fig. 4. N isotopic compositions in solar system objects, [modified from Marty et al., (13)] vary widely, showing no simple heliocentric distance trend. Genesis data (13–16) show that the Sun is like Jupiter, whereas all inner solar system samples show much larger amounts of ^{15}N . The TiN analysis 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 $^{15}\text{N}/^{14}\text{N}$ 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 $^{20}\text{Ne}/^{22}\text{Ne}$ 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 $^{36}\text{Ar}/^{38}\text{Ar}$ (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-

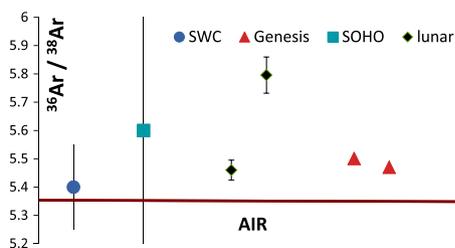


Fig. 5. Comparison of various data for solar wind Ar isotopic composition compared to that of terrestrial atmosphere (air). The Genesis data (6, 19) have error bars smaller than the symbol size and provide a precise measure of the Ar fractionation of the terrestrial atmosphere that could not be obtained 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.

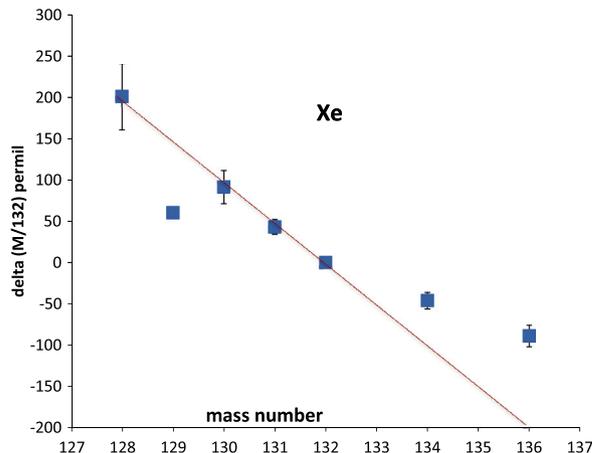


Fig. 6. Per mil deviations of Genesis solar wind Xe relative to the terrestrial atmosphere (24) have a more complex fractionation pattern than the other noble gases. Relative to an assumed mass fractionation trend from masses 128 through 131, the ^{129}Xe anomaly reflects contributions from the decay 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 $^M\text{Xe}/^{132}\text{Xe}$ 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 $^{36}\text{Ar}/^{38}\text{Ar}$; 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 $^3\text{He}/^4\text{He}$ 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 $^3\text{He}/^4\text{He}$. 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-

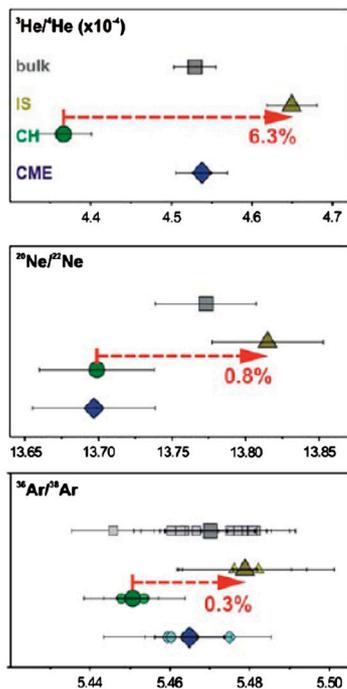


Fig. 7. Relative to bulk solar wind collectors, the Low speed (IS), High speed (CH), and Coronal Mass Ejection (CME) regime samples show precisely defined differences in the He, Ne, and Ar isotopic compositions (27).

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

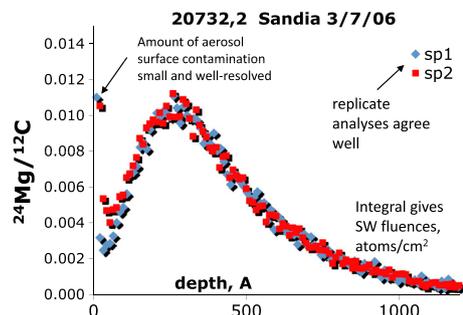


Fig. 8. Depth profile of solar wind Mg. A SIMS depth profile (Jurewicz, Guan, ASU) measures the ion counting ratio Mg/C from a diamond-like-C collector as a function of depth. Crash-derived surface contamination is clearly separated from the implanted solar wind.

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.

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1. Clayton RN (2005) O isotopes in meteorites. *Treatise of Geochemistry*, Meteorites, Comets and Planets, ed AM Davis pp:129–141.
2. Neugebauer M, et al. (2003) Genesis on-board determination of the solar wind flow regime. *Space Sci Rev* 105:661–667.
3. Wiens RC, Neugebauer M, Reisenfeld DB, Moses RW, Jr, Nordholt JE (2003) Genesis solar wind concentrator: computer simulations of performance under solar wind conditions. *Space Sci Rev* 105:601–626.
4. Mao PH, et al. (2008) MegaSIMS: a SIMS/AMS hybrid for measurement of the Sun's oxygen isotopic composition. *Appl Surf Sci* 255:1461–1464.
5. Vervoykin IV, Calaway WF, Moore JF, Pellin MJ, Burnett DS (2004) SARISA, a sputter atomized resonance ionization surface analysis instrument. *Nucl Instrum Methods* B219:473–479.
6. Heber VS, et al. (2009) Noble gas composition of the solar wind as collected by the Genesis Mission. *Geochim Cosmochim Acta* 73:7414–7432.
7. Kitts K, et al. (2009) Application of grazing incidence X-ray fluorescence technique to discriminate and quantify implanted solar wind. *J Appl Phys* 105:64905–64907.
8. McKeegan KD, et al. (2010) Genesis SiC concentrator target traverse: confirmation of ^{16}O depletion of terrestrial oxygen. *41st Lunar Plan Sci Conf* (Lunar Planetary Institute, Houston, TX) Abstract 2589.
9. Bochsler P (2000) Abundances and charge states of particles in the solar wind. *Rev Geophys* 38:247–266.
10. Clayton RN (2002) Self-shielding in the solar nebula. *Nature* 415:860–861.
11. Ayres TR, Plymate C, Keller CU (2006) Solar CO, thermal profiling, and the abundances of C, O, and their isotopes. *Astrophys J Suppl S* 165:618–651.
12. Pepin RO, Becker RH, Schlutter DJ (2009) Solar wind nitrogen in Genesis gold-on-sapphire collectors. *40th Lunar Planetary Science Conference* (Lunar Planetary Institute, Houston, TX) Abs #2103.
13. Marty B, et al. (2010) Nitrogen isotopes in the recent solar wind from the analysis of Genesis targets: evidence for large scale isotope heterogeneity in the early solar system. *Geochim Cosmochim Acta* 74:340–355.
14. Kallio APA, et al. (2010) Nitrogen isotopic of solar wind returned by the Genesis mission. *41st Lunar Planetary Science Conference* (Lunar Planetary Institute, Houston, TX) Abs #2481.
15. Huss GR, Nagashima K, Jurewicz AJG, Burnett DS, Olinger CT (2011) Isotopic composition of solar wind N in a Genesis bulk solar wind collector. *Proc. 42nd Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 1850.
16. Marty B, Chaussidon M, Wiens RC, Jurewicz AJG, Burnett DS (2011) The lowest $^{15}\text{N}/^{14}\text{N}$ end member of the solar system is the Sun. *Proc. 42nd Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 1870.
17. Meibom A, et al. (2007) Nitrogen and carbon isotopic composition of the Sun inferred from a high-temperature solar nebular condensate. *Astrophys J* 656:L33–L36.
18. Geiss J, et al. (2004) The Apollo SWC experiment: results, conclusions, consequences. *Space Sci Rev* 110:307–355.
19. Meshik A, et al. (2007) Constraints on Ne and Ar isotopic fractionation in solar wind. *Science* 318:433–435.
20. Benkert JP, Baur H, Signer P, Wieler R (1993) He, Ne, and Ar from the solar wind and solar energetic particles in lunar ilmenites and pyroxenes. *J Geophys Res* 98:13147–13162.
21. Palma RL, Becker RH, Pepin RO, Schlutter DJ (2002) Irradiation records in regolith materials II: solar wind and solar energetic particle components in He, Ne, and Ar extracted from single lunar mineral grains and from the Kapoeta howardite by stepwise pulse heating. *Geochim Cosmochim Acta* 66:2929–2958.
22. Weygand JM, Ipavich FM, Wurz P, Paquette JA, Bochsler P (2001) Determination of the $^{36}\text{Ar}/^{38}\text{Ar}$ isotopic abundance ratio in the solar wind using SOHO/CELIAS/MTOF. *Geochim Cosmochim Acta* 65:4589–4596.
23. Pepin RO (1992) Origin of noble gases in the terrestrial planets. *Annu Rev Earth Pl Sc* 20:389–430.
24. Crowther SA, Gilmour JD (2011) Solar wind Xe composition measured in Si collectors from the Genesis mission. *Proc. 42nd Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 1969.

25. Meshik AP, et al. (2011) Isotopic composition of solar wind krypton aluminum Genesis collectors. *Proc. 42nd Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 2703.
26. Bodmer R, Bochsler P (1998) The helium isotopic ratio in the solar wind and ion fractionation in the corona by inefficient Coulomb drag. *Astron Astrophys* 337:921–927.
27. Heber VS, et al. (2008) He, Ne, Ar isotopic and elemental composition of solar wind regimes collected by Genesis: implications on fractionation processes upon solar wind formation. *Proc. 39th Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 1779.
28. Humayun M, Jurewicz AJG, Burnett DS (2011) Preliminary Mg isotopic composition of solar wind from Genesis SoS. *Proc. 42nd Lunar Planetary Sci. Conf* (Lunar Planetary Institute, Houston, TX) Abstract 1211.