Invited Review

The Genesis solar wind sample return mission: Past, present, and future

D. S. BURNETT

Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
E-mail: burnett@gps.caltech.edu

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Abstract—The Genesis Discovery mission returned solar matter in the form of the solar wind with the goal of obtaining precise solar isotopic abundances (for the first time) and greatly improved elemental abundances. Measurements of the light noble gases in regime samples demonstrate that isotopes are fractionated in the solar wind relative to the solar photosphere. Theory is required for correction. Measurement of the solar wind O and N isotopes shows that these are very different from any inner solar system materials. The solar O isotopic composition is consistent with photochemical self-shielding. For unknown reasons, the solar N isotopic composition is much lighter than essentially all other known solar system materials, except the atmosphere of Jupiter. Ne depth profiling on Genesis materials has demonstrated that Ne isotopic variations in lunar samples are due to isotopic fractionation during implantation without appealing to higher energy solar particles. Genesis provides a precise measurement of the isotopic differences of Ar between the solar wind and the terrestrial atmosphere. The Genesis isotopic compositions of Kr and Xe agree with data from lunar ilmenite separates, showing that lunar processes have not affected the ilmenite data and that solar wind composition has not changed on 100 Ma time scales. Relative to Genesis solar wind, ArKrXe in Q (the chondrite noble gas carrier) and the terrestrial atmosphere show relatively large light isotope depletions.

GENESIS PAST

The Science behind the Mission

The science goals of NASA are to understand the formation, evolution, and present state of the solar system, the galaxy, and the universe. Most planetary missions investigate the present state of planetary objects. In contrast, Genesis has effectively gone back in time to investigate the materials and processes involved in the origin of the solar system by providing precise knowledge of solar isotopic and elemental compositions, a cornerstone data set around which theories for materials, processes, events, and time scales in the solar nebula are built, and from which theories about the evolution of planetary objects begin.

Solar = Solar Nebula Composition

The reason that solar abundances are important for planetary sciences rests on the assumption that the solar photosphere has preserved the average elemental and isotopic composition of the solar nebula. (There are well-known exceptions: D, ³He, very likely Li.) In turn, the solar nebula is the ultimate source of all planetary objects/materials, which are amazingly diverse. A secondary, simplifying assumption is that the solar nebula composition was uniform in space and time. These assumptions are widely, even subliminally, accepted at present and can be thought of as a kind of cosmochemical standard model. For example, we adopt the standard model when we normalize meteoritic elemental concentration data to CI chondrites. A deduction from the standard model is that large presolar nucleosynthetic isotopic variations have been

homogenized by solar nebula processes; thus, once allowance is made for nominally well-understood radiogenic and mass-dependent sources of isotopic variations, terrestrial materials can be used for average solar system isotopic compositions. This is probably true at the 10% isotopic abundance precision level overall, and much smaller levels for many elements, but cosmochemists, steeped in familiarity with O isotope systematics, know that there are major failures of the standard model, a situation that Genesis materials could clarify.

High-Precision Abundances Are Required

Solar composition is important for astrophysics and solar physics, but planetary science requires greater elemental coverage and higher levels of precision. For example, theories of stellar nucleosynthesis can be considered successful if solar system isotope ratios are reproduced to a factor of two. By contrast, isotopic measurements of terrestrial, lunar, Martian, and asteroidal materials deal with 0.1% and smaller differences.

Sample Return Is Required

The sensitivities and accuracies required for planetary science can be achieved only by analysis in terrestrial laboratories. Genesis enables measurements of solar composition by providing samples of solar wind for analysis in terrestrial laboratories. The solar wind is just a convenient source of solar matter, readily available outside the terrestrial magnetosphere. Solar wind ions have velocities in the well-understood ion implantation regime and are essentially quantitatively retained upon striking passive collectors. This was demonstrated by the highly successful Apollo solar wind foil experiments—e.g., Geiss et al. (2004)—that were an inspiration for Genesis. With almost 300 times longer exposure and, especially, with higher purity collector materials, Genesis can provide precise solar isotopic compositions and greatly improved solar elemental composition for most of the periodic table. (The Apollo foils were only sufficiently pure for the study of light noble gases.)

Essentially Nothing Was Known about Solar Isotopic Compositions

Solar isotopic compositions should be the reference point for comparisons with planetary matter. The only practical source of precise solar isotopic abundances is the solar wind. Omitting details, before Genesis, no solar, terrestrial isotopic abundance differences could be seen based on spacecraft instruments or spectroscopic observations, but uncertainties (5–40%) were too large for planetary science purposes. The Apollo foils provided precise solar wind He and Ne isotope ratios

with a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio, surprisingly, 38% greater than Ne in the terrestrial atmosphere.

Solar Elemental Abundances Can Be Greatly Improved

The observed diversity in solar system objects is chemical in origin. Quantitatively, diversity can be defined as the difference in a planetary material composition from solar composition, illustrating the importance of solar elemental abundances. The present best direct source of solar abundances comes from analysis of photospheric absorption lines in the solar spectrum (Asplund et al. 2009). A small number of elements have quoted errors of ± 10 –15% (one σ), but overall there are large uncertainties in these abundances and a significant number of elements cannot be measured at all. Thus, compilations of “solar” abundances for nonvolatile elements are currently based on analyses of carbonaceous (CI) chondrite meteorites, e.g., Palme and Jones (2004). The limitations to this have been discussed (Burnett et al. 1989; McSween 1993).

Solar Abundances Should Be Based on Solar Data

It is quite possible that a new CI fall or Antarctic find would have slightly different abundances from known CI meteorites, presenting a major challenge to how well we think we know solar abundances. If solar composition is based on solar data, we are immune from such a perturbation. The best hope for major improvement in knowledge of solar abundances is the solar wind.

Genesis Has an Important Legacy

Because planetary objects are complex and resources are limited, NASA cannot afford missions that completely characterize planetary objects. Knowledge must be accumulated incrementally, and it is likely that—in fact one should hope that—by the end of the 21st century, the information obtained with 20th century missions will be obsolete. In contrast, with a successful sample return, there did not need to be a series of solar wind sample return missions. The extent to which the crash of the Genesis sample return capsule (SRC) upon Earth return has compromised this goal is still not known. Nevertheless, it is likely that Genesis has returned a reservoir of solar matter that can be used to meet presently unforeseen requirements for solar composition. When more precise data are needed, it is likely that improved analytical techniques will be developed to meet those requirements using curated samples acquired by Genesis. The effect of the crash is to significantly increase requirements on new analytical instruments and requirements for samples cleaned of crash-derived surface contamination.

Previous Genesis science overviews can be found in Burnett et al. (2003; prelaunch) and Burnett (2011; nonspecialist review, emphasizing advantages of sample return missions).

Mission Overview

General Science Objectives

Summarizing from above, these are (1) measure solar isotopic abundances to a precision useful for planetary science purposes, (2) obtain significantly improved elemental abundances, and (3) leave a reservoir of solar matter for future generations. The above are fairly obvious. The fourth requires elaboration to a cosmochemical audience: (4) measure the isotopic and elemental composition of the three different solar wind regimes.

Solar Wind Regimes (e.g., Neugebauer 1991)

The solar wind is the expansion of the gravitationally unbound solar corona into space along open magnetic field lines. The solar corona is the outermost, high-temperature (10^6 K), tenuous part of the solar atmosphere, visible when the Sun is viewed in total lunar eclipse. Most of the energy of the Sun is emitted from the lower temperature (5500 K) “photosphere” beneath the corona. Solar wind regimes refer to the different sources of solar wind on the Sun. There are two types of solar wind flow—“quasi-stationary” and transient. There are two sources of quasi-stationary wind—*fast* wind “streaming” from coronal holes (H) and *low-speed* “interstream” (L) wind. Coronal holes are the striking dark regions in solar X-ray images and are characterized by open magnetic field lines along which outward flow of the H solar wind occurs. The origin of the L solar wind is less well understood. It may be related to release of plasma stored in small- to medium-sized closed coronal magnetic field loops when the photospheric “footprints” of these loops reconnect with field lines opening out to interplanetary space (Fisk, personal communication). Transient flows are produced by eruptions (coronal mass ejections [E]) associated with the catastrophic disruption of large magnetic field loops closed above the solar surface. A CME can have either low or high speed. The H, L, and E flows constitute distinguishable solar wind regimes. Electrostatic ion and electron analyzers (Barraclough et al. 2003) on the Genesis spacecraft (Burnett et al. 2003) measured solar wind properties to determine the solar regime present at the spacecraft using a “regime algorithm” (Neugebauer et al. 2003). Separate panels of collectors were deployed to obtain a distinct regime sample, as discussed below.

Prioritized Measurement Objectives

- (1) **O isotopes.**
 - (2) **N isotopes in bulk solar wind.**
 - (3) **Noble gas elements and isotopes.**
 - (4) **Noble gas elements and isotopes; regimes.**
 - (5) C isotopes.
 - (6) C isotopes in different solar wind regimes.
 - (7) Mg,Ca,Ti,Cr,Ba isotopes.
 - (8) **Key FIP Elements (Na, K, Mg, Fe, C, N, O, H, Ca, Cr, Al, S Si)**
 - (9) Mass 80-100 and 120-140 elemental abundance patterns.
 - (10) **Survey of solar-terrestrial isotopic differences.**
 - (11) **Noble gas elements and isotopes for higher energy solar particles.**
 - (12) Li/Be/B elemental and isotopic abundances.
 - (13) Radioactive nuclei in the solar wind.
 - (14) F abundance.
 - (15) Pt-group elemental abundances.
 - (16) Key s-process heavy elements.
 - (17) Heavy-light element comparisons.
 - (18) Solar rare earth elements abundance pattern.
 - (19) **Comparison of solar and chondritic elemental abundances.**
- Measurement of bulk solar wind except when noted.**

Fig. 1. The Genesis mission was designed around 19 “measurement objectives,” analyses that were both scientifically important and feasible. The items in bold indicate either results that have been published or measurements for which publishable data exist. Items not in bold are feasible, although difficult, and analyses have not been made.

Measurement Objectives

The original Genesis proposal plus many other project documents can be found at www.paque.com/genesis. To be more specific about what was scientifically feasible with a solar wind sample, we identified 19 specific “measurement objectives” (Fig. 1), a list of *feasible* and scientifically important measurements. Feasibility was key; many scientifically important data, such as Pb isotopic composition, Th/U, etc., did not appear to be feasible and were not listed; it is hoped that we are wrong in these assessments. Moreover, as analytical capabilities improve, important measurements not considered will be made. An example of this is D/H (Huss et al. 2012). Although deemed feasible, the measurement objectives, with few exceptions, are technically very difficult and were not feasible with instruments available in 1997. Consequently, considerable project investment was made in advanced laboratory instrumentation, some payoffs of which will be noted below. The specific science objectives associated with the measurement objectives were spelled out in the mission proposal text and in a series of appendices, which can be found at www.paque.com/genesis. Some of the specific scientific arguments from 1997 are dated, but overall are still essentially valid. The measurement objectives in Fig. 1 are a good mix of surveys (e.g., 10, 19) and focused studies addressing specific, important problems (e.g., 9, 11, 12, 14). Objectives (15) and (18) are element groups whose relative abundances figure prominently in a variety of cosmochemical applications.

Mission Systems and Operations

A series of papers in *Space Science Reviews* in 2003 (vol 105; pp. 509–679) provide a detailed and accurate description of the various aspects of the mission. All systems worked essentially as described therein, except parachute deployment, which led to the crash of the SRC on re-entry at the Utah Test and Training Range site.

Timeline

The Genesis spacecraft (Burnett et al. 2003) was launched in August 2001, reached the Sun-Earth L1 Lagrangian point, far beyond any perturbation of the solar wind by the terrestrial magnetosphere, and deployed materials beginning in December 2001. Bulk solar wind was sampled essentially continuously for a period of 853 days extending to April 2004 with Earth return on Sept 8, 2004. The details of the solar wind conditions and sampling are given in Reisenfeld et al. (2013).

Collector Arrays

Figure 2 shows a prelaunch view of the Genesis “payload” (Collector Materials plus Concentrator) at the end of assembly in a dedicated class 10 cleanroom at the Johnson Space Center (JSC). The payload was installed in a 77 cm diameter cylindrical “canister.” The canister cover was then closed, not to be opened again until at L1. The bulk of the materials were fabricated as 10 cm point-to-point hexagons and assembled in arrays. An example of an assembled collector array is shown in Fig. 3. In addition to full hexagons, the edges of the arrays were filled with half-hexagons. Nine different collector materials were selected with a view to specific analytical applications as materials of potentially high purity, so that the implanted solar wind could be seen in excess of any background impurity levels (Jurewicz et al. 2003). In some, but not all, cases, material purity and surface cleanliness were documented prelaunch. The proportions of the different collector array materials are given in Fig. 4. In addition to the hexagons, Al and Au collector (“kidney”) foils were added to fill available space (Fig. 2). Finally, the “bulk metallic glass” (BMG) (Hays et al. 2001), a material known to etch uniformly with acid, was added to the top of the array deployment mechanism (Fig. 2) for the purpose of Ne depth profiling (discussed below). Not shown in Fig. 2 are large area collectors of Mo deposited on Pt that covered the lid of the SRC installed to enable the measurement of solar wind radioactive nuclei (measurement objective 13). The SRC lid foils were severely damaged in the crash (Nishiizumi et al. 2005), but considerable progress has been made in recovering and cleaning these foils.

Fig. 2. The Genesis “payload”: collector arrays, canister, BMG (bulk metallic glass), and kidney foils. See text for detailed descriptions. The pure and clean materials were assembled in a 77 cm diameter canister in a dedicated clean room at the Johnson Space Center (JSC).

Fig. 3. Each of the arrays is composed of 54 or 55 hexagonal collectors (10 cm, point-to-point). Edges of the arrays are filled with half-hexagons. A variety of materials are used (Fig. 4).

Five collector arrays were flown. The C array was installed in the canister cover (Fig. 2). The remaining four arrays were put in a stack. Along with the C array, the topmost array in the stack (B = bulk solar wind) collected the solar wind at all times. The lower three arrays in the stack collected the regime samples. The solar wind regime at the spacecraft was determined by “monitors” (ion and electron electrostatic analyzers) on the spacecraft deck (Barracough et al. 2003) and the appropriate array deployed. From top to bottom, the regime arrays were E, H, L. A total of 346 regime deployments were made over the course of 853 days during the mission without error (Reisenfeld et al. 2013). The percentages of the regimes collected were 39.7 L, 37.3 H, and 23.0 E.

Fig. 4. The diagram shows the percentages of various collector materials used, averaged over all arrays. The detailed distribution of materials on individual rays is given in Jurewicz et al. (2003). CZ: Czochralski process single crystal Si (MEMC); FZ: float zone single-crystal Si (Unisil); SoS: epitaxial single crystal Si on sapphire (Kyocera). Ge: single crystal germanium (International Wafer Services). DOSi: Diamond-like-C layer (1 μm thick) on Si substrate, synthesized by T. Friedman, Sandia Labs. SAP: single crystal sapphire (Kyocera); AloS: e-beam-deposited high-purity Al on sapphire substrates (synthesized by A Jurewicz); AuoS: e-beam deposited high purity Au on sapphire substrates (synthesized by A Jurewicz); CCoAuoS: multilayer collector on sapphire substrates (synthesized by A Jurewicz).

Concentrator

Figure 1 shows that our six highest priority measurement objectives were isotopic analyses. Numbers 1 and 2 in priority were O and N, but in terms of solar wind fluence, material purity, and surface contamination, completion of these objectives appeared to require a higher signal-to-noise ratio than could be obtained with passive collectors. This prelaunch assessment proved to be correct. Consequently, a focusing ion telescope (“concentrator”; Fig. 5) was built to focus the solar wind incident over a diameter of 40 cm onto a “concentrator target” of 6 cm diameter, with an average concentration factor of 20 (Nordholt et al. 2003; Wiens et al. 2003, 2013; Heber et al. 2007). As shown in Fig. 6, solar wind ions first passed through the grounded front surface grid and the “H rejection grid” designed to minimize proton radiation damage to the targets. The ions were then accelerated by an additional 6.5 keV to obtain deeper implantation in the targets, compensating for the oblique angles of

Fig. 5. The concentrator is a focusing ion telescope (electrostatic mirror), designed, fabricated, and tested by Los Alamos National Laboratory (LANL; Nordholt et al. 2003; Wiens et al. 2003, 2013). Ions incident over the 40 cm diameter entrance plane of the concentrator are focused on a 6 cm diameter target in the center of the concentrator. Operation is shown in Fig. 6. Location of concentrator in payload is shown in Fig. 2.

Fig. 6. Ions incident over the 40 cm diameter entrance plane of the concentrator are focused on a 6 cm diameter target with an average concentration factor of about 20 (Wiens et al. 2013). The ground grid provides a uniform initial potential to the impinging solar wind. The H rejection grid rejects protons to minimize radiation damage to the targets. The acceleration grid provides an additional energy/charge to implant ions deeper into the targets. On passing through the domed grid, the ions see a strong repulsive potential from the electrode. As shown by the example trajectory on the figure, ions lighter than about mass 39 are reflected back through the dome grid and implanted in the target. The electrode is microstepped to provide normal incidence to photons and not reflect these onto the target.

Fig. 7. Concentrator target at time of recovery. Three of the four concentrator targets survived the re-entry crash intact (two SiC and one ^{13}C chemical vapor-deposited [CVD] diamond). The 4th diamond-like-C target was broken, but many of the broken pieces have been recovered (Rodriguez et al. 2009). The frame of the Au plated target holder ("Au cross") is labeled by clock positions. There is about a factor of nine increase in Ne fluence from edge to center. Analysis of the Ne profile in the gold cross (Heber et al. 2007) showed that the concentrator implanted ions uniformly as a function of angle.

implantation. After passing through a dome-shaped grid, the ions experience a strong repulsive force from the "mirror electrode," the potential of which was varied depending on prevailing solar wind speed. As shown in Fig. 6, the voltages were selected to reflect ions from the mirror electrode, focusing them onto the concentrator targets. Ions heavier than about mass 39 were not reflected. Ions between masses 2 and approximately 38 were focused, although fractionation effects for ions heavier than Si are significant (Wiens et al. 2013). The surface of the mirror electrode was microstepped, so that light was not focused on the target.

The concentrator target consisted of four 3 cm radius quadrants: two made of SiC, one of CVD diamond made with 99% ^{13}C , and one with the same diamond-like-C coating on Si as was used in the collector arrays. As shown in Fig. 7, three of the four quadrants survived the crash intact. The diamond-like-C quadrant broke, but around 80% of the pieces have been recovered (Rodriguez et al. 2009). With the exception of the minor failure of the proton rejection grid to achieve maximum voltage (Wiens et al. 2013), the overall concentrator performance was excellent, as documented by Ne analyses of the flight concentrator targets (Heber et al. 2011a) and the Au-coated target holder (Heber et al. 2007).

Fig. 8. The canister was badly damaged in the crash. Fragments of collector arrays were recovered with tweezers and sorted prior to shipment back to JSC. From left to right: Amy Jurewicz (ASU), Don Sevilla (JPL), Judy Allton (JSC), and Eileen Stansbery (JSC). Photograph courtesy of the Associated Press.

Consequences of Crash

The Genesis mission literally hit bottom on the morning of September 8, 2004 with the SRC crash. We began the long road to recovery by, literally, picking up the pieces, as shown in Fig. 8. The circular canister and arrays were smashed into "D" shapes with the straight part of the *D* being the plane of ground impact. With the exception of one full and a few half hexagons, all collector array materials were broken into many pieces. So, instead of 256 hexagons, we have over 15,000 irregular pieces greater than 3 mm in size (3 mm is somewhat arbitrary, representing an estimate of the smallest analyzable fragment size). Losses are considerable, but vary with material. Only a few pieces of Ge larger than 3 mm are left, but survival fractions of the strong sapphire-based collectors are much higher, e.g., greater than 64% for E array SoS (Burkett et al. 2009). Most materials are visually distinct, allowing much of the original sorting to be done at the Utah site. FZ and CZ Si are easily distinguished by transmission infrared spectroscopy, which is routinely carried out by the Genesis Curatorial Facility at JSC. The regime collector array materials were all made of different thicknesses, so regime identification was recovered. Individual sample locations on the arrays were lost, along with whether a given bulk solar wind sample was from the B or C array. Quantitative size distributions for the larger sizes (≥ 1 cm) have been made (Allton et al. 2005; Burkett et al. 2009). Finally, we were fortunate in that many special samples were retained intact: the concentrator targets (Fig. 7), the BMG, and the kidney foils, although the Al kidney was severely warped.

GENESIS PRESENT

This section presents an overview of published Genesis science results. We are proud that a lot has been accomplished, but consequently, to provide a survey, this review will primarily focus on results. More extensive interpretations can be found in the papers cited. Model implications are beginning to emerge (e.g., Huss 2012; Ozima et al. 2012).

Solar Wind Isotope Fractionation: Evidence from Light Noble Gases in Regime Samples

Prior to Genesis, elemental fractionation between the solar wind and photosphere was well established from spacecraft instrument data (e.g., von Steiger et al. 2000), but, as discussed below, these fractionations were ordered by first ionization potential (FIP), which meant that isotopic variations were not necessarily expected. Figures 9a–c show clearly resolvable differences in the isotopic compositions of He, Ne, and Ar in the different solar wind regimes (Heber et al. 2012). The variations in Fig. 9 are relatively small; however, the Inefficient Coulomb Drag model of Bochsler (2000) predicts that the isotopic variations *among* regimes are much less than the overall fractionation of *any* solar wind sample from the Sun (Fig. 10). The Bochsler model predicts that solar wind isotopic variations correlate with solar wind He/H (an elemental ratio), and it is well established from spacecraft instruments that solar wind He/H is lower than the photosphere by approximately a factor of two. The amount of fractionation between the Genesis low- and high-speed solar winds (Fig. 9) is close to that predicted by Bochsler (Heber et al. 2012).

O Isotopes in the Solar Wind

The large (30% range in $\delta^{18}\text{O}$) nonmass-dependent variations in O isotopes in meteoritic materials are a major failure of the standard model and remain unexplained. Locating the solar (i.e., average solar nebula) composition on the O three-isotope plot was the top priority measurement objective for Genesis. This was the main driver for building the concentrator. Genesis funding also developed the MegaSIMS, a hybrid mass spectrometer combining a standard sputter ionization system with a high-energy (MeV) accelerator mass spectrometer (Mao et al. 2008). The investment in these two flight instruments—one launched, one not launched—paid off (Figs. 11 and 12; McKeegan et al. 2011). Figure 11 shows a blowup of the ^{16}O -rich region of the three-isotope plot with the MegaSIMS data for one of the SiC concentrator targets. The terrestrial mass fractionation and CAI lines are shown for reference.

Fig. 9. Variations are seen among the bulk and two of the three solar wind regime samples for the isotopic compositions of He, Ne, and Ar (Heber et al. 2012). Here, H = high-speed solar wind, L = low-speed solar wind; Bulk represents the total solar wind collected from December 2001 through April 2004. These data provide the best evidence that the solar wind fractionates isotopes. a) $^3\text{He}/^4\text{He}$. b) $^{20}\text{Ne}/^{22}\text{Ne}$. c) $^{36}\text{Ar}/^{38}\text{Ar}$. Error bars are 1 sigma and smaller than the points for He. The differences between the low- and high-speed solar wind decrease with mass. The H–L differences agree with the Bochsler model predictions (Fig. 10).

The concentrator fractionates isotopes, with fractionation varying as a function of radial distance from the center (Wiens et al. 2013), but a correction is possible based on measurements of $^{22}\text{Ne}/^{20}\text{Ne}$ as a

Fig. 10. In the Bochsler (2000) model, collisions between accelerated protons and heavier ions produces a mass-dependent fractionation that correlates with the amount of fractionation of He and H. $(4/3) = {}^4\text{He}/{}^3\text{He}$; $(18/16) = {}^{18}\text{O}/{}^{16}\text{O}$; $(22/20) = {}^{22}\text{Ne}/{}^{20}\text{Ne}$; $(26/24) = {}^{26}\text{Mg}/{}^{24}\text{Mg}$. Curves show the predicted heavy isotope decrease in the solar wind as a function of the He/H ratio of the solar wind sample. The vertical line indicates the Genesis bulk solar wind (BSW) H/He (Reisenfeld et al. 2013). Based on a solar He/H ratio of 0.084 from helioseismology, fractionations can be predicted, e.g., about 6% depletion for ${}^{18}\text{O}/{}^{16}\text{O}$. Curve based on calculations by R. Wiens.

function of position on the same SiC concentrator target (Heber et al. 2011a). The corrected analyses from different concentrator positions agree, giving a $\Delta^{17}\text{O}$ (vertical displacement from TF in Fig. 11) of -28.4 ± 1.8 permil. This is a model-independent result and shows that solar and terrestrial O isotopic compositions are very different, a nontrivial finding.

As shown by the light noble gas regime data (Fig. 9), significant O isotope fractionation between the Sun and the solar wind is possible. This fractionation is almost certainly mass-dependent, with the Sun having a higher $\delta^{18}\text{O}$ than the solar wind, as shown by the dotted line on Fig. 11. The literal prediction of the Bochsler model (Fig. 10) lies somewhat beyond the CAI line, but, as argued by McKeegan et al. (2011), it is likely that the Bochsler model overcorrects, and so the best estimate is that the solar composition lies on the CAI line, a result consistent with the photochemical self-shielding model (originally from Clayton 2002). Figure 12 shows the solar point in relation to other inner solar system materials. The existence of rare samples, more ${}^{16}\text{O}$ -rich than the Sun (Kobayashi et al. 2003), is not impossible, but deserves more study. I find the combination of the ${}^{16}\text{O}$ -rich solar composition and some highly ${}^{16}\text{O}$ -depleted water (Sakamoto et al. 2007) a compelling argument for photochemical self-shielding, indicating a plausible pathway for ${}^{17}\text{O}$ and ${}^{18}\text{O}$ atoms

Fig. 11. Data points are the measured solar wind O isotopic compositions from a SiC concentrator target (McKeegan et al. 2011). Units are deviation of measured isotope ratio from that of ocean water in permil (parts per thousand). Data measured as different radial positions agree when corrected for concentrator mass fractionation, defining the solar wind O isotopic composition. When the Sun–solar wind mass fractionation correction from the Bochsler model (Fig. 10) is applied, the composition indicated by the solid asterisk is obtained. McKeegan et al. argue that the Bochsler prediction is slightly too large and that the actual solar O isotopic composition lies on the CAI line as shown by the star. TF = mass-dependent fractionation trend for terrestrial samples.

produced from CO dissociation to enter essentially all inner solar system materials (Lyons and Young 2005; Lyons 2013). One must admit, however, that the “essentially all” requirement is a problem for photochemical self-shielding and this has led to alternative models based on inherited differences in O isotopic composition between gas and dust in the original solar nebula materials (e.g., Krot et al. 2010; Huss 2012).

Solar Nitrogen Isotopic Composition

Prior to Genesis, it was known that there were wide variations (factor of three) in the ${}^{15}\text{N}/{}^{14}\text{N}$ ratio in solar system materials (e.g., Kerridge 1995). With only two isotopes, it was not possible to cleanly distinguish mass-dependent and mass-independent (e.g., unmixed residues from stellar nucleosynthesis). However, the variations seemed far too large for standard mass-dependent processes based on knowledge of terrestrial mass-dependent N isotopic variations. The amounts of N in lunar regolith samples were much higher than in lunar rock samples not exposed to the solar wind, so it was assumed that solar wind exposure was the source of the

Fig. 12. This is fig. 4 of McKeegan et al. (2011) comparing the Genesis solar O isotopic composition (Fig. 11) with other solar system materials. Units are deviation of measured isotope ratio from that of ocean water in permil (parts per thousand). References for the data plotted can be found in McKeegan et al. Except for one chondrule, all inner solar system materials are richer in ^{17}O and ^{18}O than the Sun with a fixed proportion of the heavier isotopes. This is qualitatively in accord with self-shielding models.

lunar regolith sample N. However, the measured $^{15}\text{N}/^{14}\text{N}$ ratios varied by up to about 40%, which was very difficult to explain. SIMS analyses on rock surfaces (e.g., Hashizume et al. 2000) indicated that the solar wind was at, or below, the low end of the measured lunar $^{15}\text{N}/^{14}\text{N}$ range. It was also known, based on NH_3 absorption lines (Fouchet et al. 2000; Abbas et al. 2004) and on the Galileo entry probe mass spectrometer (Owen et al. 2001), that the $^{15}\text{N}/^{14}\text{N}$ for the Jupiter atmosphere is 40% lower than the terrestrial atmosphere.

Figure 13 compares the Genesis solar value of $^{15}\text{N}/^{14}\text{N}$ (Marty et al. 2011) with other solar system materials. The Genesis $^{15}\text{N}/^{14}\text{N}$ ratio is low, agreeing with Jupiter, with an anomalous CB chondrite TiN grain (Meibom et al. 2007), and with meteoritic nanodiamonds (e.g., Russell et al. 1996). Note that the scale in Fig. 13 is *percent*, not permil. Thus, as with O, the N isotopic composition of most of inner solar system shows a large difference from the Sun, a second major violation of the standard model.

Unlike O, one can compare the solar and inner solar system N isotopic compositions with objects in the outer solar system. Figure 13 shows that a simple inner–outer solar system difference is not present; the difference seems to be the Sun and Jupiter versus almost everything else.

Fig. 13. There are large variations in the N isotopic composition in the solar system. Note that units are percent, not permil. With the exception of an anomalous TiN grain (Meibom et al. 2007) and meteoritic nanodiamonds (Russell et al. 1996), the Genesis solar wind N isotopic composition is much lower than all inner solar system materials. Four different Genesis analyses agree; the most precise from Marty et al. (2011) is shown by the solid line. The solar $^{15}\text{N}/^{14}\text{N}$ ratio is predicted to be about 3% higher than the solar wind, a small difference on this plot. Overall, the N isotopic composition does not correlate with distance from the Sun. The Jupiter value appears solar, but Titan and cometary CN or HCN have much higher $^{15}\text{N}/^{14}\text{N}$. These differences are unexplained at present. Other data from Kerridge (1995), Hashizume et al. (2000), Owen et al. (2000), Mathew et al. (2003), Taylor et al. (2004), Niemann et al. (2005), Bockele-Morvan et al. (2008).

Based on the Genesis results, the $^{15}\text{N}/^{14}\text{N}$ for Jupiter is solar. As discussed below, the He and H isotopes in Jupiter's atmosphere also appear solar. But, C/H and N/H are enriched to about 4× from solar (Taylor et al. 2004). If the C/H and N/H enrichments are due to infalling planetesimals, as often discussed, these planetesimals are very different from comets and Titan (Owen et al. 1999). However, the Titan and comet data on Fig. 13 are probably not representative of outer solar system materials. The $^{15}\text{N}/^{14}\text{N}$ of Titan has probably been increased by atmospheric loss, and the measured comet molecules, HCN and CN, may only represent a small fraction of the overall comet N inventory. Alternatively, the planetesimal infall model might be wrong. The Jupiter atmospheric C and N could come from a rock-ice core of solar composition onto which Jupiter gas accreted.

The Genesis N isotope data prove that the lunar regolith contains large extralunar, but nonsolar, contributions to N, most likely from comets and asteroids (Hashizume et al. 2000). The same is probably true of C, although the issue of gravitational escape of

Table 1. Bulk solar wind He and Ne isotopic composition (2 sigma errors).

	$^3\text{He}/^4\text{He}$ (10^{-4})	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$
Apollo solar wind ^a	4.3 ± 0.25	13.7 ± 0.3	0.033 ± 0.003
Genesis bulk solar wind ^b	—	13.97 ± 0.03	—
Genesis bulk solar wind ^c	—	14.00 ± 0.04	0.0336 ± 0.0002
Genesis bulk solar wind ^d	4.64 ± 0.09	13.78 ± 0.03	0.0329 ± 0.0001
Lunar ilmenite ^e	4.57 ± 0.08	13.8 ± 0.1	0.0328 ± 0.0005
Terrestrial atmosphere ^f	— ^g	9.80 ± 0.08	0.0290 ± 0.003
Chondrite trapped, Q^f	1.43 ± 0.02	10.1–10.7	0.0293

^aGeiss et al. (2004).^bAl on sapphire collector; Meshik et al. (2007).^cAu collectors; Pepin et al. (2012).^dDLC = diamond-like-C collector; Heber et al. (2009).^eBenkert et al. (1993). Lunar sample 71501.^fBusemann et al. (2000).^gHe not bound in terrestrial atmosphere.

C (and N) atoms following impact (Ganapathy et al. 1970) needs to be revisited. Extralunar sources for noble gases in lunar regolith samples have not been recognized, although the focus of lunar regolith noble gas studies (following section) has been on isolating clean samples of unmodified solar wind noble gases. Only a few meteoritic whole-rock analyses (e.g., Kerridge 1995) show enrichments greater than 20%. Excluding these, the meteorite/asteroidal $^{15}\text{N}/^{14}\text{N}$ approximately matches the upper bound of the lunar data without invoking cometary contributions; however, this is possibly misleading because the presence of solar wind N lowers the measured $^{15}\text{N}/^{14}\text{N}$ in a whole-rock lunar regolith sample. The enriched $^{15}\text{N}/^{14}\text{N}$ samples contain the most information about the extralunar components. However, the most common N-rich CI and CM chondrites show relatively small enrichments (0–5%), so that materials with larger enrichments of $^{15}\text{N}/^{14}\text{N}$ are required (comets?).

Unlike noble gases, the amounts of N contributed by identified presolar grains are negligible in the analysis of bulk meteoritic samples. However, meteoritic nanodiamonds (e.g., Russell et al. 1996) are depleted in $^{15}\text{N}/^{14}\text{N}$ by 35%, very close to the Genesis solar wind depletion of $38.3 \pm 0.5\%$. Because they contain anomalous Xe H-L, the nanodiamonds have been regarded as presolar, but the close correspondence of their $^{15}\text{N}/^{14}\text{N}$ with solar (Genesis) suggests that these have a solar system origin (Meibom et al. 2007) with Xe H-L arising from a minor carrier within nanodiamond samples.

The large N isotopic variations in meteoritic materials (e.g., Kerridge 1995) may arise from photochemical self-shielding. Both from theory and laboratory experiments, photodissociation rates of N_2 are high, so this is a viable mechanism for the large ^{15}N enrichments in meteoritic materials. (Clayton 2011; Shi et al. 2012).

The post-Genesis interpretation of terrestrial $^{15}\text{N}/^{14}\text{N}$ is deferred until after consideration of noble gases.

Overall, the origins of the N isotopic variations on Fig. 13 are poorly understood.

Bulk Solar Wind Noble Gas Isotopic Compositions

Many authors have noted the uniqueness of O as an element, which is partitioned in comparable amounts into the gas and dust phases of the solar nebula, whereas most other elements are almost entirely in one of the two phases. There is also a correlation with isotopic variations. Very broadly speaking (i.e., omitting CAIs), “nonvolatile” elements show small (permil and smaller) variations. Volatile elements are more complex; O, N, and noble gases show large variations, whereas variations in C, S, and Cl are smaller.

In terms of solar noble gas isotopic composition, a rich literature exists on solar wind noble gases implanted in lunar soils (e.g., as summarized by Ozima et al. 1998), but as also recognized, lunar processes introduce significant complications into the data, e.g., for N as discussed above. And, as expected, having a “clean” solar wind sample from Genesis has led to significant clarifications.

Table 1 compares various measured solar wind He and Ne isotopic compositions with those obtained by closed-system etching of lunar soil ilmenite samples (e.g., Benkert et al. 1993), the terrestrial atmosphere, and Q, the host phase of noble gases in chondrites (e.g., Busemann et al. 2000).

The high-precision solar wind Genesis $^3\text{He}/^4\text{He}$ (Table 1) from Genesis diamond-like-C samples agrees well with the mean Apollo solar wind composition (SWC) foil result at the 2σ level, and is also very close to the $^3\text{He}/^4\text{He}$ derived from the initial releases from

closed system etching of ilmenite from lunar soil breccia 71501 (Benkert et al. 1993).

Solar evolution models predict that an early convective (“Hayashi”) phase would completely destroy solar D, converting it to ^3He . This greatly enhances the solar $^3\text{He}/^4\text{He}$, as first pointed out by Geiss and Reeves (1972). Thus, the D/H ratio in the solar wind, from Genesis data, is less than about 10^{-7} (Huss et al. 2012), compared to about 1.5×10^{-4} on Earth. In the atmosphere of Jupiter, $\text{D}/\text{H} = 2.6 \pm 0.7 \times 10^{-5}$ (Taylor et al. 2004), which is probably the best estimate of the primordial solar nebula value. In the case of H, the assumption of initial solar nebula isotopic homogeneity is not obviously valid, e.g., did the solar bipolar outflow stage reintroduce D-depleted and ^3He -enriched gas back to the nebula? Gravitational accretional energy is almost certainly being released in the Hayashi phase, which presumably means bipolar outflow as well. In X-wind models (Shu et al. 1997), CAIs and chondrules are returned to the nebula, but is the amount of gas returned negligible? The D/H systematics in the solar system are strikingly similar to $^{15}\text{N}/^{14}\text{N}$ (Marty et al. 2011), a similarity worthy of further consideration.

The Jovian $^3\text{He}/^4\text{He} = 1.66 \pm 0.05 \times 10^{-4}$ is the best estimate available of the pre-D-burning solar nebula ratio, which compared with the value in Table 1, indicates an enrichment of a factor of 2–3 in the solar wind $^3\text{He}/^4\text{He}$ by D burning. Calculation of the exact enrichment factor must allow for solar–solar wind He isotope fractionation. This is discussed by Heber et al. (2009), but in any case, the solar $^3\text{He}/^4\text{He}$ enhancement appears compatible, within errors, with the Jovian D/H. The lower $^3\text{He}/^4\text{He}$ of chondrite Q relative to the Jovian value (Table 1) is worthy of further study.

The Genesis measurements of $^{20}\text{Ne}/^{22}\text{Ne}$ (Table 1) are within the uncertainty range of the Apollo SWC foils. Although there is a discrepancy among different Genesis measurements, this is small compared with the major differences between any solar wind measurement and the terrestrial atmosphere. This large difference, long recognized based on the Apollo SWC data, has been interpreted as reflecting Ne isotopic fractionation accompanying loss of the terrestrial atmosphere (Pepin 2006). The relation between solar wind Ne isotopes and Q is discussed below.

The agreement in both the He and Ne isotopic composition between Genesis and the lunar sample 71501 ilmenite confirms that ilmenite gives the best data for solar wind composition from lunar samples. This is important for He in that almost all lunar samples exhibit serious He loss. Moreover, as the 71501 data represent solar wind sampled over a 10^8 yr period, comparison with Genesis shows no measurable

compositional changes in the solar wind over this time period. This is one issue for which the disagreement among the Genesis $^{20}\text{Ne}/^{22}\text{Ne}$ measurements is a significant complication.

The small, but significant, difference among the Genesis $^{20}\text{Ne}/^{22}\text{Ne}$ measurements illustrates an important strength of sample return missions. Present-day robotic missions cannot afford redundant measurements, even for high-priority measurements. However, sample return missions not only give data, but because the standard scientific method (reproducibility in this case) is affordable, data can be verified to be correct and realistic errors assigned, as illustrated by the Ne isotopes in Table 1.

Heavy Noble Gases

Figures 14–16 give a systematic comparison of Genesis heavy noble gas (ArKrXe) isotopic compositions with Q, the carbonaceous host phase of chondritic noble gases (Busemann et al. 2000) and with the terrestrial atmosphere (air). Here, I make only a simple comparison: Q or air compared with mass-dependent fractionated solar wind noble gases. The issues raised by Figs. 14–16 have an extensive literature going back over 30 yr beginning with Lewis et al. (1975). The discussion here in no way represents a comprehensive review of models for the origins of the measured isotope fractionations. I only discuss the simplest possible model, but previously proposed by Ozima et al. (1998); more complex models are generally regarded as necessary, e.g., Gilmour (2010) or Meshik et al. (2012, 2013).

To the extent that Genesis has confirmed the solar wind noble gas abundances derived from the study of selected (primarily ilmenite) lunar regolith materials, it can be argued that nothing has changed. However, there is a big change: we now know for sure—and to a high level of accuracy—that unrecognized lunar processes or nonsolar external sources are not present in the lunar solar wind noble gas isotopic abundances. Contrast the situation to that of N (and probably C) where much of what is measured in lunar regolith samples, contrary to original expectations, is not from the solar wind.

Moreover, the close agreement between Genesis and lunar ilmenite solar wind heavy noble gas isotope abundances shows that the solar wind composition has remained constant over time scales of roughly 100 Ma.

Before considering details, it is worth emphasizing that, relative to the solar wind, both Q and air show qualitatively consistent depletions in the lighter isotopes.

Three Genesis measurements of $^{36}\text{Ar}/^{38}\text{Ar}$ (Fig. 14) agree well and also agree with one of the two previous

Fig. 14. Three independent measurements of Genesis solar wind $^{36}\text{Ar}/^{38}\text{Ar}$ agree (one sigma error bars smaller than symbol size). The Genesis data agree with the lunar regolith data of Benkert et al. (1993), but differ from those of Palma et al. (2002). The Apollo solar wind composition foils (Geiss et al. 2004) and the SOHO spacecraft data (Weygand et al. 2001) agree, but with much larger errors. The Genesis data show that the solar wind $^{36}\text{Ar}/^{38}\text{Ar}$ is significantly higher than air as well as Q, the trapped noble gas component in chondrites (Busemann et al. 2000).

literature values for solar wind implanted into lunar regolith samples. The error bars from a spacecraft instrument analysis and from the Apollo SWC foils are too large to show a clear difference with the terrestrial atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$ ratio, but the Genesis data clearly show that ^{36}Ar in air is depleted by 17 ± 2 permil amu^{-1} relative to bulk solar wind Ar. This is in the same sense, but much smaller than the 200 permil amu^{-1} depletion of ^{20}Ne in air compared to ^{22}Ne . The air $^{36}\text{Ar}/^{38}\text{Ar}$ ratio is close to that of Q.

The Genesis Xe and Kr isotopic data plotted on Figs. 15 and 16 are from Meshik et al. (2012, 2013). The Genesis Xe isotopic composition from Crowther and Gilmour (2012) is in agreement with Meshik et al.

The fractionations in Kr isotopic compositions of Q and air are similar; both show larger depletions with decreasing mass relative to Genesis solar wind composition. However, the fractionation patterns on Figs. 15a and 15b are not obviously well described by a constant permil/amu factor. With data over 8 mass units (10% in mass for Kr) and a total range of variation of 100 permil, a constant fractionation factor would not necessarily be expected for mass-dependent fractionation processes, e.g., adsorption or atmospheric loss. However, the fractionations would be expected to

Fig. 15. a) Fractional deviation in permil of Kr in Q, the trapped noble gas component in chondrites (Busemann et al. 2000) from the Genesis solar wind Kr isotopic compositions (Meshik et al. 2012, 2013) calculated as: $([M/84]_Q/[M/84]_{SW} - 1) \times 1000$ with $M = \text{Kr}$ isotopic mass. Error bars are propagated from errors on the Q and solar wind data. Errors are 1 sigma. As a reference to assess possible mass-dependent mass fractionation relations, the dashed line is fit to masses 82 and 84. Except for a clear deviation at mass 86, the Q versus solar wind fractionation pattern is describable by constant permil amu^{-1} . b) Same format as (a), but for fractionation of air Kr from solar wind. At the 2 sigma level, air Kr can be related to Genesis solar wind Kr by a light isotope-depleted fractionation of about 8 permil amu^{-1} .

be smooth functions of mass difference. A simple way to assess smoothness is to draw “midmass reference lines” as a guide to the eye on Figs. 15a and 15b between two isotopes in the center of the mass range and look for deviations from this. We have chosen ^{82}Kr and ^{84}Kr . This choice is arbitrary, although ^{82}Kr and ^{84}Kr are primarily s-process isotopes. For the amount of Q fractionation relative to the solar wind (Fig. 15a), the reference line corresponds to about 9 permil amu^{-1} , a large amount of fractionation for a heavy element.

Fig. 16. a) Fractional deviation in permil of Q Xe, the trapped noble gas component in chondrites (Busemann et al. 2000) from the Genesis solar wind Xe isotopic compositions (Meshik et al. 2012, 2013) calculated as: $([M/132]_Q/[M/132]_{sw} - 1) \times 1000$ with $M = \text{Xe}$ isotopic mass. Error bars are propagated from errors on the Q and solar wind data. Errors are 1 sigma. As a reference to assess possible mass-dependent mass fractionation relations, the dashed line is fit to masses 130 and 132. The anomaly at mass 129 represents contributions to Q from ^{129}I decay. The radiogenic 129 contributions to solar Xe are much less because of the much lower solar I/Xe. It is likely that there are significant excesses in Q from mass-fractionated solar Xe for the lightest and heaviest Xe isotopes, but the large errors for masses 124 and 126 for the solar wind analyses prevent strong conclusions at present. b) same format as for (a) for fractionation of air Xe from Genesis solar wind. The anomaly at mass 129 represents contributions to air from ^{129}I decay. It is likely that there are significant excesses in air from mass fractionated solar Xe for the lightest Xe isotopes. The heaviest Xe isotopes at masses 134 and 136 are depleted relative to the midmass trend. These deviations are poorly understood. The choice of the midmass fractionation line for Xe may be a poor choice for comparison.

The reference fractionation line for air is only slightly less, around 8 permil amu^{-1} .

On Fig. 15a for Q versus solar wind, at masses 78 and 80, the measured fractionations are low compared with the reference line, but at 2σ limits of error. At mass 86, the measured fractionation is much greater than the reference line. The overall fractionation pattern is not especially smooth. For the comparison of air versus solar wind (Fig. 15b), the deviations at 78 and 80 are below, but within error of, the reference line. Similarly, the measured fractionations at 83 and 86 are close to the line, so that, overall, air and solar wind Kr are close to being related by a constant 8 permil amu^{-1} fractionation

For Xe, both Q and air show excesses at mass 129 attributable to the effect of ^{129}I decay in reservoirs with lower Xe/I than the Sun. For the remaining isotopes, we adopt a midmass reference line between masses 130 and 132 for assessment of mass-dependent fractionation effects (Figs. 16a and 16b).

Relative to the reference 10 permil amu^{-1} fractionation line, there are probably large excesses for both the lighter and heavier Xe isotopes in Q relative to solar wind (Fig. 16a). Although the errors at masses 124 and 126 for the Genesis data do not permit a clean distinction, the basic pattern is set by excesses at masses 128 and 136.

For the air–solar wind comparison (Fig. 16b), the reference line fractionation is very large, 45 permil amu^{-1} , with the measured fractionations above the reference line for the light isotopes and below the line for the heavy Xe isotopes.

Use of the clean solar wind sample from Genesis has not resulted in a simpler picture of the relations among solar wind, Q, and air Xe. It appears difficult to account for the differences between solar wind and both Q and air Xe isotopic compositions as due to mass-dependent fractionation from solar wind Xe, as suggested by Ozima et al. (1998).

The above comparisons are relative to Genesis solar wind noble gas compositions. Additional corrections are required for fractionations between the Sun and the solar wind. From Fig. 10, based on the Inefficient Coulomb Drag model, the estimated correction for Ne would decrease the measured solar $^{20}\text{Ne}/^{22}\text{Ne}$ by about 15 permil amu^{-1} and $^{36}\text{Ar}/^{38}\text{Ar}$ by roughly 8 permil amu^{-1} . The fractional effect on Ar is more important. The Inefficient Coulomb Drag fractionations decrease strongly with increasing mass, and are probably not important for Kr and Xe. So, although possibly important for detailed modeling, e.g., of atmospheric escape, the solar wind data can be regarded as close enough to solar for present purposes.

Summary: Mass-Dependent Heavy Noble Gas Isotope Fractionation?

Table 2 summarizes the permil amu^{-1} mass fractionation of Q and air relative to the solar noble gas and N isotope composition. The midmass permil amu^{-1} trend is used for Xe and Kr. The consistent light isotope depletions suggest that mass-dependent fractionation is at least part (although only part) of the overall measured fractionations, although a variety of mechanisms (adsorption, atmospheric escape, etc.) might be involved. There are many interesting comparisons in Table 2, including some that do not make a lot of sense. With effectively only two isotopes, Ne and Ar provide no constraints on whether the fractionation processes were mass-dependent, except possibly that the required amounts of fractionation for Ne (and N) for air are very large. The amounts of Ar fractionation for both Q and air compared with Ne appear small. The relative fractionations for Ar and Kr for both Q and air appear plausible and suggest some commonalities in origin. Compared with Kr, the amounts of fractionation of Xe appear far too large for both air and Q. The midmass slopes of the Xe patterns from mass 130 to 132 define permil amu^{-1} fractionations that are much larger for air than for Q. The air Xe permil amu^{-1} fractionation for Xe is larger than Kr, which is very unreasonable, although the use of the midmass fractionation as reference may be inappropriate for Xe. The overall fractionation patterns for Xe appear incompatible with mass-dependent processes, although the fractionation pattern for air Kr (Fig. 15b) is close to a constant permil amu^{-1} fractionation. There is still much to be understood about air noble gases, Xe in particular.

Terrestrial Atmospheric Escape

Some terrestrial mantle samples (e.g., Tieloff et al. 2000) have $^{20}\text{Ne}/^{22}\text{Ne}$ ratios approaching the solar wind value of 13.8, at least as high as 12.5. This has generally been interpreted as indicating that the Earth accreted from materials containing solar Ne, but that the atmospheric escape processes early in Earth's history preferentially lost ^{20}Ne , decreasing the ratio to the present value of 9.8 (Pepin 2006). However, an alternative view interpreting air Ne as a mixture between solar wind Ne and the "Neon A" component from carbonaceous chondrites has been proposed by Marty (2012).

Atmospheric loss processes for Venus and Mars appear to have increased the D/H by orders of magnitude (data compiled by Robert et al. 1999), but the terrestrial D/H, although increased over the Jupiter

Table 2. Isotope fractionations (permil amu^{-1}) relative to solar wind.^a

Element	Q	air
N	—	683
Ne	163	204
Ar	15	17
Kr	9	8
Xe	10	45

^aLight isotope depleted in all cases. Fractionations are calculated in a consistent way for $I = Q$ or $I = \text{air}$ as $([M_1/M_2]_I/[M_1/M_2]_{\text{sw}} - 1) \times 1000$ with M_1 heavier than M_2 . For Kr and Xe, midmass slopes of the fractionation patterns are tabulated. The Kr permil amu^{-1} is between 82 and 84. The Xe permil/amu fractionation is based on masses 130–132. Overall, for both Kr and Xe, Q versus solar wind and air versus solar wind fractionation patterns are not describable by constant permil amu^{-1} .

value by a factor of 5–7, is much lower than the Mars or Venus atmosphere and is essentially the same as that observed for the hydrated silicates in CI or CM chondrites, which are unlikely to have been affected by atmospheric escape. The difference between H and Ne can be explained if, as today, there is an atmospheric cold trap that removes H_2O from the top of the atmosphere where the loss occurs.

Genesis data show that the $^{15}\text{N}/^{14}\text{N}$ ratio in air is 68% higher than the solar wind (Table 2). Correction for solar wind–solar isotope fractionation would increase this difference further, but only by a few%. The air–solar $^{15}\text{N}/^{14}\text{N}$ difference is in the right sense (light isotope depleted) for atmospheric loss. The amount of isotope fractionation for N is in the right direction, but potentially too large relative to the (already high) 200 permil amu^{-1} from Ne (Table 2). Whether or not greater or smaller amounts of fractionation are expected for N relative to Ne depends on whether the escaping species is N or N_2 . But, in any case, if Ne isotopes are affected by atmospheric escape, N should be as well as there is nothing equivalent to an atmospheric cold trap for N.

There is no evidence for light solar N in terrestrial mantle samples (e.g., Marty and Dauphas 2003). Also, atmospheric escape does not explain the high $^{15}\text{N}/^{14}\text{N}$ ratios in many meteoritic materials relative to the Sun. Finally, to the extent that the noble gas isotopic compositions of air have been affected by early escape of the terrestrial atmosphere, the similarities in the fractionation factors between air and Q in Table 2 for NeArKr are surprising. If, as mentioned above, the solar-meteoritic differences in $^{15}\text{N}/^{14}\text{N}$ can be explained by photochemical self-shielding, then the Earth–solar differences can also be explained.

Much remains to be understood about N and noble gas isotopic compositions in the Earth's atmosphere.

Fig. 17. a) Ne isotopic variations during a stepwise closed system etching experiment on ilmenite mineral separates from lunar soil breccia 71501 (Benkert et al. 1993). Numbers on data points are etch steps. A systematic decrease in $^{20}\text{Ne}/^{22}\text{Ne}$ is observed with no increase in $^{21}\text{Ne}/^{22}\text{Ne}$ until the point marked SEP is reached, at which point the increase in $^{21}\text{Ne}/^{22}\text{Ne}$ marks the beginning of release of cosmogenic Ne. Many other lunar samples showed a similar trend that was interpreted as mixing between solar wind Ne (SWC) and a higher energy solar component (SEP). Figure 17a used with permission of American Geophysical Union. b) Stepwise closed system etching experiment analogous to (a) on the Genesis bulk metallic glass (BMG, Fig. 2; Grimberg et al. 2006). The release pattern is very similar to that of (a), but here it can be accounted for by the fractionation of Ne isotopes during implantation, as shown by the SRIM implant model prediction. Without knowledge of actual depths analyzed in lunar samples, the release pattern was misinterpreted. There is no SEP.

Ne Depth Profiling: SEP RIP

The literature on lunar regolith noble gases prior to 2006 contains extensive discussion of a higher energy solar particle component referred to as “solar energetic particles (SEP).” The SEP was inferred from Ne isotopic patterns in stepwise release experiments using closed system acid vapor etching. In a typical lunar release pattern, as shown in Fig. 17a from Benkert et al. (1993), the initial steps show a Ne isotopic composition in agreement with the Apollo SWC (or Genesis) average bulk solar wind composition. Subsequent etching gives progressively lower $^{20}\text{Ne}/^{22}\text{Ne}$ with decreasing $^{21}\text{Ne}/^{22}\text{Ne}$ until, with large amounts of etching (step 14 and beyond in Fig. 17a), excess amounts of ^{21}Ne associated with galactic cosmic ray (GCR) spallation reactions are observed, terminating the correlation observed in the earlier release steps. The early release correlation was convincingly interpreted as two-component mixing between solar wind, as observed in the Apollo SWC foils, and higher energy solar SEP particles with $^{20}\text{Ne}/^{22}\text{Ne}$ about 11.2. The Genesis BMG (Fig. 2) was selected to be uniform and acid vapor-etchable to test for SEP in the contemporary particle flux. As Fig. 17b, from Grimberg et al. (2006), shows, progressive acid vapor etching of the BMG gave a *solar*

wind Ne isotope release pattern that closely resembled that from lunar regolith samples. This was not expected. Moreover, the BMG variations could be quantitatively reproduced by calculations of the isotopic fractionation resulting from difference in the implantation depth profiles of the three Ne isotopes. At depths of 200–300 nm, both the measured and calculated *solar wind* $^{20}\text{Ne}/^{22}\text{Ne}$ reach the range of the inferred SEP component and, in some analyses, actually go below the SEP $^{20}\text{Ne}/^{22}\text{Ne}$. The measured variations in lunar regolith samples can be understood in terms of isotopic fractionation during solar wind implantation without invoking any higher energy solar component. The ability to quantitatively depth profile a Genesis sample with simple exposure history, especially no GCR Ne, resulted in essentially instant clarification.

There were no dissenters; we all believed in SEP. Why? Speaking only for myself, even if I had done the implantation calculation (which I didn't), the lunar regolith data are better fit by the two-component mixing model. There is actually a striking difference in the data on Figs. 17a and 17b in that many points in the BMG data have $^{20}\text{Ne}/^{22}\text{Ne}$ higher than the average solar wind $^{20}\text{Ne}/^{22}\text{Ne}$. This is expected from ion implantation fractionation, as shown in Fig. 17b. Initial releases with $^{20}\text{Ne}/^{22}\text{Ne}$ higher than 14 were rarely seen in lunar data,

and when observed, were not given the attention they deserved. Without any knowledge of the actual depths of etching of the lunar samples, I could easily assume that the first etching steps released *all* of the solar wind Ne and that the lower $^{20}\text{Ne}/^{22}\text{Ne}$ data were coming from micron-deep levels. The similarities in the initial lunar sample releases and the bulk solar wind $^{20}\text{Ne}/^{22}\text{Ne}$ can be understood if one assumes equilibrium between sputter erosion and implantation (Wieler et al. 2007).

It is often, somewhat cynically, said that NASA missions raise more questions than they answer. The Genesis SEP studies show that sample return missions can solve problems, once and for all. Similarly, the Hayabusa mission has, once and for all, settled the issue of what S asteroids are.

GENESIS FUTURE

The parts of the measurement objectives (Fig. 1) that are highlighted in bold type include measurements where publishable data are available beyond the published results discussed in the previous section. Preliminary reports on many of these are found in Lunar Planetary Science abstracts.

Elemental Analyses; FIP/FIT Fractionations

The objectives of Genesis solar wind elemental analysis are discussed in the above section beginning with Solar Elemental Abundances. The situation for elements differs from that for isotopes: (1) Unlike isotopes, for which there were essentially no previous data, compositional data from solar photospheric absorption lines and analyses from CI chondrites are available for comparison. (2) Elemental fractionations of the solar wind relative to the photosphere were known from spacecraft instrument data.

Solar wind elemental composition is presented in terms of normalized abundance plots. A fractionation factor, F , is defined:

$$F = (E/\text{Mg})_{\text{sw}} / (E/\text{Mg})_{\text{ph}} \quad (1)$$

Mg is the reference element, sw refers to solar wind, and ph to the photosphere.

Figure 18 shows F from the Ulysses spacecraft for low- and high-speed solar wind (von Steiger et al. 2000). There are two common ways to plot solar wind-normalized abundances: against FIP or against FIT (first ionization time). FIP is a measured atomic property; FIT is model-dependent, being an estimated time required for a neutral atom rising out of the solar photosphere to be ionized as it enters the solar corona and eventually the solar wind. The resulting patterns are

Fig. 18. Fractionation factor, F , defined as the ratio of the element to Mg divided by the same ratio in the photosphere from Asplund et al. (2009). Data for fast and slow solar wind from the Ulysses/solar wind ion composition spectrometer (von Steiger et al. 2000) are plotted versus a model first ionization time (FIT, Reisenfeld and Wiens, personal communication). Easily ionized elements appear unfractionated, but elements with higher FIT are depleted in the solar wind relative to the photosphere. High FIT elements are also more depleted in the slow solar wind.

qualitatively similar, as FIT and FIP tend to correlate; however, there are also differences as the FIT–FIP correlation is not perfect. I prefer FIT as it is a better expression of the physical mechanism behind the observed fractionations, but its model dependence is a problem.

The major features of Fig. 18 are not dependent on whether FIP or FIT is used.

On Fig. 18, low-FIT elements (equivalent to $\text{FIP} < 9$ eV) have $F = 1$, i.e., appear to be unfractionated. All of the nonvolatile elements that make up inner solar system bodies have $\text{FIP} < 9$ eV. This is a clear model-independent target for Genesis: we are testing for a flat pattern of photospheric-normalized abundances for low-FIP elements. Errors in both the solar wind instrument and photospheric abundances are both typically 15–20% for traditional major elements. Replacing the solar wind instrument with Genesis data will result in more precise predictions, but we can never avoid the need for accurate photospheric abundances.

The higher FIT elements in Fig. 18 are depleted, i.e., more difficult-to-ionize elements tend to be left behind during extraction of the solar wind from the photosphere. Inferring photospheric abundances for high-FIT elements is challenging, but this is an important task for several reasons. To mention one example, the C, N, O photospheric abundances, which had quoted errors of 10–15%, decreased by about 50% with the advent of 3-D photospheric models (e.g., Asplund et al. 2009). But, the new photospheric C, N, O

abundances disagree with those inferred from helioseismology (Basu and Antia 2008). This decade-long disagreement is an area where Genesis–solar physics collaboration will be very fruitful. We can provide more accurate data on solar wind CNO abundances than the solar physics community has had previously, including isotopic compositions. Furthermore, we have separate samples of the three major types (regimes) of solar wind. We anticipate that the CNO abundances in the different regimes will vary. The regimes represent different physical processes on the Sun (Neugebauer 1991), so different theories will be required. But, the three different theories are required to converge on single values for the photospheric CNO abundances. This should be a powerful constraint on the accuracy of the derived photospheric CNO abundances.

CONCLUSIONS: LOOKING FORWARD

Analysis of Genesis samples is actively being pursued. Looking beyond 2013, important measurements of C isotopes, Mg isotopes, Na/KNi fluences, FIT/FIP fractionation plots for bulk and regime samples, etc. will be made.

In general, referring back to Fig. 1, *none* of the original measurement objectives appears to not be feasible. The Genesis Mission met the official NASA Mission Success Criteria several years ago. The fundamental reason that, despite the SRC crash, the Genesis Mission can be considered a success is illustrated in Fig. 19, which shows SIMS depth profiles for solar wind Mg in a diamond-like-C collector. The solar wind is implanted below the surface that contains the crash-derived contamination. The peak of the solar wind is separated from the surface contamination by 30 nm. This is a small distance, but it is many atom layers in the collector material. The crash destroyed materials, but it could not destroy solar wind atoms. They are safely contained in the surviving materials.

In terms of analyses, the clear resolution of contamination and solar wind shown in Fig. 19 is not always achieved. For ion beam analyses using small (about 100 μm) spots, backside depth profiling (Heber et al. 2010, 2011b) has been very successful.

Genesis samples contain a flight-derived thin contamination film (“brown stain”) of polymerized silicone (Allton et al. 2006). Photoelectron spectroscopy measurements show that brown stain thickness is highly variable from 0 to a maximum of 5 nm, with most samples less than 2 nm; solar wind attenuation is negligible for these thicknesses. When necessary, the brown stain can be removed by uv-ozone treatment (Sestak et al. 2006). Brown stain has ended up being more of a nuisance than a threat.

Fig. 19. SIMS bulk solar wind depth profile for Mg in diamond-like-C collector. Two separate profiles (sp1 and sp2) agree well. This plot demonstrates that solar wind is separated from surface contamination resulting from the re-entry crash. Data courtesy of A. Jurewicz and R. Hervig.

Crash-derived particulate contamination is a major problem. The biggest challenge is in large (cm size) area analysis where, in the worst cases, a 1–10 μm contaminant particle can contribute as much of a given element as the solar wind. For this reason, a major cleaning study has been initiated, organized through the Genesis Curatorial Facility at JSC (Allton et al. 2007; Rodriguez et al. 2013). The cleaning study aims to learn how to decontaminate surfaces to meet the requirements of specific analyses.

The cleaning study illustrates another major advantage of sample return missions. When problems arise, in our case contamination from the SRC crash, all of modern (and as the ultimate recourse, future) science and technology can affordably be brought to bear to solve the problems. And, of course, as new techniques and problems arise, the samples are here, without a new mission.

Acknowledgment—This review is an expansion of the 2012 Leonard Medal address. The success of Genesis was a team effort, involving the work of hundreds of individuals. Management, payload design, and mission operations were carried out at the Jet Propulsion Laboratory (JPL). Spacecraft and recovery were carried out by Lockheed Martin Astronautics (Denver). Payload integration and postcrash recovery was smoothly executed by a JPL-JSC partnership. Contingency planning by the JSC Genesis Curatorial staff made possible the rapid postcrash recovery. A 2011 tabulation of scientists who worked on the planning, implementation, recovery, and analysis

phases of the Genesis Discovery mission is available at www.pnas.org/content/suppl/2011/05/06/1014877108.DCSupplemental. I have benefitted from discussions as part of the Solar Wind Composition Working Group sponsored by the International Space Sciences Institute (ISSI, Bern). Important advice on this manuscript from Amy Jurewicz, Alex Meshik, Charles Hohenberg, Roger Wiens, and Julie Paque is gratefully acknowledged. Helpful reviews were obtained from A. Davis and an anonymous reviewer. This work was sponsored by NASA LARS grant: NNX09AC35G.

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