Solar and Solar-Wind Isotopic Compositions

Roger C. Wiens[1]
Peter Bochsler[2]
Donald S. Burnett[3]
Robert F. Wimmer-Schweingruber[4]

[1]Space and Atmospheric Sciences
Mail Stop D466
Los Alamos National Laboratory
Los Alamos, NM 87544
rwiens@lanl.gov
505-667-3101

[2]Physikalisches Institut
University of Bern
Sidlerstrasse 5
CH-3012 Bern, Switzerland

[3]Department of Geology
Mail Stop 100-23
California Institute of Technology
Pasadena, CA 91125

[4]Institut fuer Experimentelle und Angewandte Physik,
University of Kiel,
Leibnizstrasse 11,
D-24118 Kiel, Germany

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Abstract

With only a few exceptions the solar photosphere is thought to have retained the mean isotopic composition of the original solar nebula, so that, with some corrections, the photosphere provides a baseline for comparison of all other planetary materials. There are two sources of information on the photospheric isotopic composition: optical observations, which have succeeded in determining a few isotopic ratios with large uncertainties, and the solar wind, measured either in-situ by spacecraft instruments or as implanted ions into lunar or asteroidal soils or collection substrates. Gravitational settling from the outer convective zone (OCZ) into the radiative core is viewed as the only solar modification of solar-nebula isotopic compositions to affect all elements. Evidence for gravitational settling is indirect, as observations are presently less precise than the predictions of < 10‰ effects for the isotopes of solid-forming elements. Additional solar modification has occurred for light isotopes (D, Li, Be, B) due to nuclear destruction at the base of the convection zone, and due to production by nuclear reactions of photospheric materials with high-energy particles from the corona. Isotopic fractionation of long-term average samples of solar wind has been suggested by theory. There is some evidence, though not unambiguous, indicating that interstream (slow) wind is isotopically lighter than high-speed wind from coronal holes, consistent with Coulomb drag theories. The question of fractionation has not been clearly answered because the precision of spacecraft instruments is not sufficient to clearly demonstrate the predicted fractionations, which are < 30‰ per amu between fast and slow wind for most elements. Analysis of solar-wind noble gases extracted from lunar and asteroidal soils, when compared with the terrestrial atmospheric composition, also suggests solar-wind fractionation consistent with Coulomb drag theories.

Observations of solar and solar-wind compositions are reviewed for nearly all elements from hydrogen to iron, as well as the heavy noble gases. Other than Li and the noble gases, there is presently no evidence for differences among stable isotopes between terrestrial and solar photosphere compositions. Although spacecraft observations of solar-wind isotopes have added significantly to our knowledge within the past decade, more substantial breakthroughs are likely to be seen within the next several years with the return of long-exposure solar-wind samples from the Genesis mission, which should yield much higher precision measurements than in-situ spacecraft instruments.

Keywords
Solar wind, solar abundances, solar nebula

Glossary

CME	Coronal mass ejection: episodic explosive release of coronal material frequently carried within closed magnetic field loops.
Coulomb drag	An aspect of solar-wind acceleration theory referring to the acceleration of heavier species by ionized hydrogen that is escaping from the photosphere.
FIP fractionation	Elemental abundances in the solar wind are fractionated (the ratios of their abundances are modified) during ionization and acceleration according to the first ionization potential (FIP) of each element. Low FIP elements are preferentially accelerated.
High-speed streams	Fast solar wind characterized by He/H ratios of ~0.045 and by relatively low elemental fractionation, emanating from cooler, UV-dark regions of the corona, as evidenced by low charge state ions in the stream. High-speed streams are usually 600-800 km/s at 1 AU.
Interstream wind	Low-speed wind characterized by relatively high elemental fractionation, emanating from relatively hot regions of the corona. Interstream wind is always < 600 km/s and often < 400 km/s.
L1 point	The metastable Lagrangian point 1.5 million km sunward of the Earth.
LSCRE	Lunar Surface Cosmic Ray Experiment: Cosmic ray exposure experiment developed by Washington University. On Apollo 17 it included a platinum solar wind exposure foil.
OCZ	Outer convection zone: the outer third of the Sun by radius, where heat is transferred to the surface by convection. The composition of the OCZ is often referred to as "solar" composition.
Permil (‰)	Deviations in parts per thousand relative to a given standard. Example: $\delta^{15}\text{N} = -50$‰ means a 5% depletion of ^{15}N relative to $^{15}\text{N}/^{14}\text{N}$ in the standard.
Regolith	Layer of loose incoherent material at the surface of a planetary body. "Soil."
SEP component	A noble-gas and nitrogen component of lunar and meteoritic regolith grains that is more deeply buried than the solar-wind component.

Solar gravitational settling	Differential effect of gravity on elements and isotopes of different mass. It results in a depletion of heavy species in the OCZ.
Solar nebula	Disk of gas and dust from which the solar system was formed.
SWC	Solar Wind Composition experiments, developed by the University of Bern, consisted of specialized foils exposed to the solar wind for periods of hours to ~2 days during the Apollo lunar missions.
Wave-particle interactions	Interactions between electromagnetic waves in the solar-wind plasma and its particles which can modify the velocity distributions of the particles.

Spacecraft

ACE	Advanced Composition Explorer, launched August, 1997 to an L1 halo orbit and currently operating.
Genesis	NASA mission returns samples in September, 2004 of solar wind collected on high-purity substrates over a period of two years at L1.
ISEE-3	International Sun-Earth Explorer 3, launched in 1978, was the first space probe to use the L1 point for solar observations.
SOHO	SOlar and Heliospheric Observer, launched in December, 1995 to an L1 halo orbit and currently operating.
Ulysses	Joint NASA and European Space Agency mission launched in 1990 to study the polar regions of the Sun and the 3-D structure of the heliosphere.
Wind	NASA mission launched in 1994 to study plasma mass, momentum, and energy properties in the upstream near-Earth regions as part of the Global Geospace Science program.

Introduction

The isotopic composition of the sun's outer convection zone (OCZ) is of very great interest to planetary science because it is relatively unchanged in composition from the solar nebula, the starting material of the solar system. The solar nebula, and by extension, the OCZ, can be used as a baseline for comparison of present-day planetary, asteroidal, meteoritic, atmospheric, and cometary isotopic compositions. Studying compositional differences relative to the original solar nebula is one of the few ways we have of understanding the evolution of our solar system. Unfortunately, very little information on the OCZ isotopic composition is directly available from astronomical data (e.g., [1-6]). The alternative to direct solar observations is the measurement of solar-wind isotopic compositions, the main subject of this paper.

In order to use the solar-wind compositions to infer nebular isotopic compositions, important considerations must be made in two major areas. One is modification of the OCZ relative to the original solar nebula, and the other is modification of solar-wind compositions relative to the OCZ. In the first area, major modifications to the OCZ relative to its precursor nebular composition are a) nuclear destruction and production of some light isotopes, and b) some amount of gravitational settling from the OCZ to the radiative zone below. Both of these issues have been indirectly substantiated, but experimental confirmation of the extent of these processes via solar-wind measurements is interesting in its own right. Gravitational settling has been confirmed by the improvement of the model seismic velocities with observed helium abundances. These models predict fractionation on the order of 33‰ for ^{3}He/^{4}He, 5‰ for δ^{13}C, 4‰ for δ^{15}N, 3‰ per amu for the oxygen isotopes, dropping gradually with increasing mass number to ~1‰ per amu for iron [7,8]. Observational constraints indicate that nuclear burning of light isotopes during the fully convective stage of solar evolution resulted in complete loss of deuterium, a factor of ~140 depletion in lithium and a beryllium loss of less than a factor of two (e.g., [9]).

In the second area of consideration, modification of solar-wind compositions relative to the OCZ, solar-wind compositions are known to be variable over short time scales. Long-term samples of solar wind may have substantial isotopic fractionation relative to the OCZ. Significant advances have recently been made in understanding this issue, as will be discussed in the section describing solar-wind characteristics.

If a true solar nebula isotopic composition can be inferred from the solar wind or by any other means, the topics of interest are numerous, and span a number of isotopic systems. The isotopic precision desired to answer these questions spans a range, depending on the topic, but is generally from ±10‰ to ±0.1‰. The Genesis mission, which in September, 2004 returns 2-year samples of collected solar wind, promises to enable high precision solar-wind isotopic measurements for the first time. This paper reviews the state of knowledge just prior to this important sample return. The two critical areas reviewed are: what we know about the recently-emerging issue of solar-wind isotopic fractionation, and what we can infer for the solar composition from the most recent solar-wind measurements. Application of the new high-precision Genesis measurements is discussed in the final section of the paper.

Measurements of Isotopes in the Sun and Solar Wind

Solar and solar-wind measurements come from four sources: one is direct solar photospheric observations and three sources involve measurement of the solar wind in various ways. The photospheric observations are of D/H, He, CO and Li absorption lines, which have yielded some information on their isotopic compositions [1-6]. The three solar-wind sources consist of: i) measurements of solar wind collected in the Solar-Wind Composition (SWC) and Lunar Surface Cosmic Ray Experiment (LSCRE) foil experiments of the University of Bern and Washington University during the Apollo missions [10]. ii) solar-wind measurements made on samples of planetary regoliths—both lunar soils and mineral grains from gas-rich meteorites which were exposed to solar wind and compacted and ejected from their parent body regolith, and iii) solar-wind measurements made since the late 1970s for helium first on ISEE-3 and then Ulysses, and since the mid-1990s for heavier isotopes using time-of-flight (TOF) sensors on WIND, ACE, and SOHO spacecraft. Because of the potential complications involved in interpreting solar energetic particle data, they are not included in our discussion.

The solar wind foil experiments yielded isotopic information on solar wind ^{3}He/^{4}He, ^{20,21,22}Ne, and ^{36}Ar/^{38}Ar obtained over brief periods between 1.25 and 45 hours, from Apollo 11 to Apollo 17. The Apollo 17 measurement is reported here for the first time. These measurements are still more precise than can be obtained by spacecraft instruments. However, each foil exposure was for only a short duration, making these measurements subject to short-term variations in solar-wind composition, as discussed below. Historically these measurements were a watershed in that they established that terrestrial atmospheric neon is distinctly different from solar, laying the foundation for studying the role of hydrodynamic escape in the atmospheric evolution of the terrestrial planets. Measurements of solar wind in planetary regoliths suffer from parent-body effects which must be removed to determine the true solar-wind composition. This deconvolution has become increasingly more effective, so that for noble gases the regolith analyses now provide the most accurate measurements of solar-wind composition. Another advantage of regolith measurements is their uniqueness in allowing studies of the constancy of solar-wind compositions through time. A disadvantage is their limitation mostly to measurements of noble gases.

In-situ measurements by the MASS sensor on the SMS instrument on the Wind spacecraft, the MTOF sensor on the CELIAS instrument on SOHO, and the SWIMS instrument on ACE have been made on a wide variety of elements up to and including iron [11-13]. Using these instruments, measurements where the dynamic range between two isotopes is less than 100 yield results with uncertainties generally at or somewhat under 100 permil. Isotope ratios with dynamic ranges between 100 and 600 (e.g. δ^{15}N, δ^{18}O) yield results with larger uncertainties, while isotope ratios with dynamic ranges > 600 (e.g., δ^{17}O) have not been reported. Low abundances rule out the study of Li, Be, B, as well as elements heavier than about mass 60, e.g., heavier than iron group elements.

Table 1 is a compilation of solar and solar-wind isotopic compositions, given with 1-σ uncertainties except where noted. This table will serve as the basis for discussions below.

Solar Wind Characteristics

To infer solar compositions from solar-wind measurements, it is crucial to understand many of the characteristics of the solar wind that result in the potential for compositional differences between it and the OCZ.

The solar wind is the continuous flow of ionized plasma streaming outward from the sun along magnetic field lines. Solar wind elemental compositions are known to be fractionated relative to the photosphere. The primary fractionation occurs in the ionization process; with the result that fractionation is a function of the elements' first ionization potential (FIP). Elemental fractionation is weakest in high-speed streams, with a factor of one to two enrichment of low FIP over high FIP elements relative to the photosphere. In low-speed (interstream) wind elemental fractionation is greater and more variable, at factors of 2.5-5 [14,15]. A transient state of the solar wind, coronal mass ejections (CMEs), exhibits highly variable composition that, if not accounted for, makes the determination of solar composition difficult because it can contaminate measurements in the other solar-wind streams. We will therefore not consider the composition of CMEs in this work.

The FIP by itself does not affect isotopes, but there may be other, underlying mechanisms that result in isotopic fractionation. For example, the differential velocities of various species in the corona [16] have lended support to solar-wind acceleration models based on the opposing forces of gravitation and Coulomb drag, which predict isotopic fractionation. Wave-particle interactions may also contribute to fractionation effects, though if the effects are transient, long-term solar-wind samples may avoid these effects. In the Coulomb drag concept [17], the solar wind acceleration process proceeds through multiple collisions with electromagnetically accelerated protons. Inefficiencies in this process cause heavier species to be left behind. In these models the fractionation relative to H of a species of mass number A and atomic charge q scales as $(2A – q – 1)*[(1+A)/A]^{1/2}*q^{-2}$. These models predict significant isotopic fractionation of up to 300‰ for ^{3}He/^{4}He and -50‰ for δ^{18}O, with similar fractionation/amu for other heavy ions as mentioned for oxygen. Fractionation in high-speed wind is predicted to be significantly less, at ~85‰ for ^{3}He/^{4}He and -17‰ for δ^{18}O [7,18,19]. However, as will be shown below, observational evidence for differences of this magnitude between high-speed and interstream material is still somewhat ambiguous.

Solar-wind variability. Temporal variations in solar-wind fractionation result in compositional variability. Solar wind helium isotopes measured on one-hour timescales exhibit order-of-magnitude variations, but long-term averages tend to converge. For example, the average of hourly sampling of ^{4}He/^{3}He from the ISEE-3 Ion Composition Instrument (ICI) over a 3.4 year period from 1978-1981 (2050±200) is within uncertainty of the average of the Apollo SWC results (2350±120) which represent about 5 days total exposure near solar maximum. Daily averages from Ulysses over 500 days in 1992-1993 yielded similar results (2290±200) [20]. Here the ± represents variability of the data, independent of systematic error estimates. Thus, despite short-term variability, there appears to be a well-defined long-term average value for ^{4}He/^{3}He, and by extension, the same is assumed for the isotopes of heavier elements. In fact, heavier elements show significantly less isotopic variability than ^{4}He/^{3}He even in short-term measurements. The Apollo solar-wind foil data show >25% variation in helium isotopes, but only ~5% variation in ^{20}Ne/^{22}Ne among the six different samples [10].

Constraints on Solar-Wind Isotopic Fractionation. Are time-averaged measurements, for which short-term variability is averaged out, isotopically fractionated relative to the photosphere? The existence and magnitude of solar-wind isotopic fractionation must be determined by either a) correlations between isotopes in different parcels of solar wind (e.g., isotope correlations for different collection periods), or by b) comparison of isotopes between different types of solar wind which would be expected to be fractionated differently. Both techniques are discussed here. The Apollo foil experiments give relatively accurate measurements of different parcels of solar wind collected over three years, but specific details of the solar wind dynamics that would help determine the type of solar wind are lacking. On the other hand, in-situ spacecraft have allowed comparisons of long-term average compositions for high-speed versus interstream wind.

The Apollo foil experiments yielded unsurpassed information on the light noble gas isotopes in terms of a measurement of pure solar wind—not extracted from a planetary regolith--with uncertainties of as little as ±30‰ for an individual measurement. The Apollo foils collected solar wind predominantly during periods of low speed solar wind. Figure 1 shows ^{4}He/^{3}He vs. ^{20}Ne/^{22}Ne data for collection periods made during each of the lunar landings, including the Apollo 17 results first published here (^{4}He/^{3}He = 2000±105; ^{20}Ne/^{22}Ne = 13.55±0.50; F. Bühler, personal communication). Also shown in Fig. 1, the fractionation predicted by the Coulomb drag model matches the slope of the best fit linear correlation to the Apollo foil data, though the uncertainty for the linear correlation is quite large, allowing a complete absence of fractionation or fractionation in the other direction. Based on Fig. 1, a current best estimate of the photospheric ^{20}Ne/^{22}Ne ratio using both data and theory is 13.35±0.80.

Using spacecraft data, He as well as heavier elements, particularly Ne, Mg, and Si, have recently been studied for indications of isotopic mass fractionation between fast and slow wind. Figure 2 shows various reported ^{4}He/^{3}He ratios, some at different wind speeds. The ISEE-3 ^{4}He/^{3}He ratio for v > 450 km/sec (1900±200) was within errors the same as the average for all speeds [21]. Ulysses has alternately sampled interstream wind and high-speed streams. Reports over the first several years of the mission (e.g., [18,20,22] suggested no systematic variation with solar-wind speed. However, more recent analyses [23-26] have reached the opposite conclusion. The difference appears to be the result of a change in the relative weighting placed on data from different collectors [23]. With this new interpretation, Geiss and Gloeckler [23,24,26] recently used correlations of ^{4}He/^{3}He with the elemental ratios of He/H and Si/O in two high-speed periods and two interstream periods, chosen based on ion charge state, to derive photospheric ^{4}He/^{3}He ratios of 2620 and 2670 respectively, about 15% higher than the long-term average ratios measured in the solar wind (Table 1). The trend in the isotopic data of Geiss and Gloeckler confirms the expectations from the Coulomb drag models.

Data from heavier elements measured by spacecraft instruments are more ambiguous. Figure 3 shows a three-isotope plot of Mg for a 17-month period from December, 1994 to May, 1996 as measured by the MASS instrument on WIND [27], and for a 7-month period as measured by MTOF on SOHO during 1996 [28]. Aside from He, Mg is the easiest test for fractionation with spacecraft instruments, as it has three relatively abundant isotopes. The data were separated into two bins by velocity, with the dividing line at 400 km/s. The high-speed stream is within uncertainty of the terrestrial ratio. But the nominal value for the low-speed wind is fractionated in favor of the heavy isotope, opposite of that suggested by the Coulomb drag models [7,18,19], although the error bars easily permit interpretation in either direction. Other data from in-situ solar wind measurements have suggested that the heavy isotopes are indeed depleted in low-speed wind for silicon (e.g., [29]), but in essentially all cases the uncertainties leave room for both interpretations.

In summary, the data from the Apollo foils, to which we attribute the highest reliability, are consistent with solar-wind isotopic fractionation (Fig. 2), as are the recently published helium isotopic results. Still, in comparing all data in Table 1, due to the large uncertainties and lack of agreement between different observations, one cannot conclude that a fractionation trend has clearly been discovered, nor can we conclude the absence of a trend. A top priority of the Genesis mission will be to determine the presence or absence of solar-wind isotopic fractionation.

Discussion: Solar and Solar-Wind Isotopic Abundances

An accurate database of the OCZ isotopic composition is useful for understanding the initial inputs to the solar nebula, providing a baseline for the planetary, asteroidal, and cometary compositions. In addition it is important for understanding the current and ancient solar surface environment, for which issues are important such as gravitational settling out of the convective zone, deep solar mixing, and the solar radiation environment controlling production of rare isotopes at the solar surface. Here we review recent results for both solar and solar-wind data sets. In many cases the precision of the solar wind measurements is not so great that the unsolved question of solar-wind isotopic fractionation causes a problem. The exceptions are the noble gases, for which He and Ne have already been discussed in the context of isotopic fractionation.

D/H and ^{4}*He/*^{3}*He.* These ratios are key parameters for pre-solar conditions, including galactic evolution and parameters for big bang nucleosynthesis. The primordial deuterium is thought to have been destroyed at the base of the convection zone, where the temperature is sufficient to cause nuclear burning. A discussion of flare-produced D is given in a later section. The early solar destruction of D produced ^{3}He directly, significantly modifying the solar ^{4}He/^{3}He. As expected, the Galileo probe ^{4}He/^{3}He ratio for Jupiter is much higher than the solar wind ratios, with a value of 6000±200 [30]. This ratio is the best available estimate of the nebular ^{4}He/^{3}He, although if liquid helium rainout occurred in the interior of Jupiter, it could have produced significant ^{3}He enrichment in the atmosphere. Several factors may have worked to modify the photospheric ^{4}He/^{3}He ratio relative to primordial ^{4}He/(^{3}He$_i$+D), where the denominator is the sum of initial ^{3}He plus deuterium. These factors include gravitational settling and the addition of ^{3}He produced via the p-p reaction at greater depths. A recent investigation [31] of He and Ne in lunar grains suggests the absence of a temporal trend, leading to a conclusion that primordial ^{4}He/(^{3}He$_i$+D) was the same as the present OCZ ^{4}He/^{3}He. Recent estimates put the (D/H)$_i$ ratio at 19.7±3.6 ppm based on solar data, and 21±4 based on Jovian data [26].

Oxygen and Carbon. The oxygen isotopic ratio of the OCZ has been suggested to hold important clues to the formation of the solar nebula (e.g., [32] and references therein). The solar-wind δ^{18}O values reported so far from in-situ measurements are 110^{+450}_{-250}‰ for slow wind [33] and 120^{+280}_{-190}‰, 2-σ, for fast wind [34], relative to standard mean ocean water (SMOW). At present the uncertainties of these measurements do not constrain them to be different from terrestrial. The δ^{18}O value reported for direct solar photospheric molecular measurement over sunspots, at 130^{+145}_{-115}‰ [5], is nearly identical to the nominal solar wind values, but with the smaller uncertainties it is slightly heavy relative to SMOW at the 1-σ level. Figure 4 shows solar-wind δ^{18}O values in comparison with other solar-system materials. Meteoritic materials are typically displayed on a 3-isotope plot, including the δ^{17}O. However, there are currently no measurements of solar δ^{17}O. For δ^{18}O, bulk meteoritic values lie between -5 and +25 ‰, while oxygen in calcium-aluminum inclusions in chondritic meteorites has been measured to be as depleted in ^{17}O and ^{18}O as -60 ‰. The single measurement of cometary water ice [35,36] is also shown.

The carbon isotopic ratio was also reported from solar CO absorption lines. The two values vary widely, at δ^{13}C = -60±100‰ [3] and $+59^{+67}_{-60}$‰ [5] relative to the terrestrial standard, but both essentially overlap with the bulk terrestrial carbon. No solar-wind carbon isotopic measurements have been reported from spacecraft, as distinction from ions released from the carbon foils used in these instruments is difficult. Surface-correlated carbon in bulk lunar soils falls in the range of ±30‰. Carbon abundances are higher than expected relative to solar-wind noble-gas abundances in lunar soils, suggesting that the bulk of the surface-correlated C is not solar wind. A recent ion probe study found δ^{13}C values as light as -105‰, leading the authors to suggest that solar-wind carbon is at least this depleted in ^{13}C [37]. For comparison, Fig. 4 shows the Jovian atmospheric carbon value of -57±44‰ [38]. Cometary CN observations [39] give even lighter values (-460^{+170}_{-105}, -225^{+160}_{-115}), below the scale of Fig. 4. The context of these recent isotopically light measurements is unclear at this time.

Nitrogen. The solar-wind nitrogen isotopic ratio has long been of interest as a baseline for planetary atmospheric compositions. The lunar soils have trapped and retained nitrogen regarded initially as being implanted solar wind. However, analyses of bulk lunar soils have yielded a range of approximately 400‰ in isotopic compositions, while the abundance of N is typically enriched by up to an order of magnitude relative to noble gases when normalized to solar abundances. One interpretation was that a) nitrogen is more efficiently retained in lunar soils and noble gases are partially lost, and along with this, b) a secular change in the solar-wind nitrogen isotopic composition was postulated. However, the higher nitrogen abundance and the fact that it varies from grain to grain in a given sample [40] strongly suggested domination by a larger, non-solar-wind component. Hashizume et al. [41] recently reported a correlation between δ^{15}N and D/H in ion probe analyses, which they used to distinguish solar contributions (e.g., trending towards an absence of deuterium) from planetary contributions, e.g., from micrometeorite bombardment. Their results showed that isotopically light nitrogen correlated with low deuterium content. As solar wind is considered to be deuterium-free, this suggests that solar-wind nitrogen is depleted in ^{15}N by at least 240‰ relative to the terrestrial atmosphere.

Nitrogen is at the limits of what can be reasonably measured by in-situ spacecraft instruments due to the large difference in abundances between ^{15}N and ^{14}N. An early report [42] of isotopically heavy solar-wind nitrogen has recently been revised to 30±500‰ [43], consistent with all other N measurements. Besides the photosphere, another potential reservoir of primordial nitrogen gas is the atmosphere of Jupiter. Figure 4 shows two Jovian measurements, one made telescopically [44] and one from the Galileo probe mass spectrometer [45,46]. Both measurements give an isotopically light composition relative to terrestrial, suggesting that the solar ratio is more like that measured in lunar soils than the nominal value of the relatively uncertain in-situ solar-wind measurement. Cometary observations indicate that nitrogen in CN is isotopically heavy, off the plot in Fig. 4, but HCN is isotopically light, as shown in Fig. 4 [39 and references therein]. Measurement of the solar-wind nitrogen by Genesis is eagerly anticipated, as it could confirm or reject the agreement of the solar composition with most of these other solar-system nitrogen reservoirs, and decide whether the Earth's atmospheric composition is enriched in ^{15}N relative to the solar nebula.

Solar surface isotope production: D, ^{6}Li, ^{10}Be, and ^{14}C. Abundances of several rare isotopes, including radioactive isotopes, have been inferred from observations of the solar surface and measurements in the solar wind. These species can potentially constrain the extents and timescales of mixing in the upper portion of the solar convective zone. At present these include D, Li, ^{10}Be, and ^{14}C. Although deuterium is destroyed at the base of the OCZ, it is produced by radiative capture of neutrons which are a by-product of energetic particle events, and in the most energetic events D can also be produced directly by proton-proton collisions. Constraints on the D/H ratio by lunar samples limit the minimum solar-wind D/H ratio to less than ~7 ppm, or around -950 ‰ [41] based on individual measurements, and to < 3 ppm (-980‰) based on correlations [47]. Attempts to spectroscopically detect deuterium in the solar atmosphere have had mixed success, as reviewed recently in [2]. Early observations over sunspots [1] produced an estimate of D/H ~ 100 ppm, while other observations over the quiet solar surface failed to detect D. Mullan and Linsky [2] noted that solar D has been observed in solar energetic particles, but so far not directly in the solar wind.

Lithium is depleted by a factor of ~140 in the photosphere relative to C1 meteoritic abundances. This depletion was postulated to be due to nuclear destruction of lithium at the base of the OCZ. In the absence of any other inputs this process would be expected to leave the remaining lithium strongly enriched in ^{7}Li relative to the original ^{7}Li/^{6}Li ratio of 12, the chondritic and terrestrial value. Optical observations of lithium absorption lines have been made in regions above sunspots, where lower ionization facilitates their observation. Reported values are consistent with the enhancement of this ratio, constraining it to be > 33 [6]. The observation appeared to measure some ^{6}Li, with a most probable ^{7}Li/^{6}Li ratio of ~50, well below that expected if the factor of 140 depletion in elemental abundance were due solely to nuclear destruction without any additional inputs [6]. An attempt was recently made to measure the ^{7}Li/^{6}Li ratio of the solar wind concentrated in the outer layers of lunar grains. Chaussidon and Robert [48] reported an extrapolated ratio of 31±4 after correcting for contamination and spallation reactions induced by energetic particles in the lunar soil. They explained this ratio as the result of a combination of nuclear destruction at the base of the OCZ with addition of lithium with a ^{7}Li/^{6}Li ratio of ~2 produced by spallation reactions involving solar energetic particles and carbon and oxygen in the solar atmosphere. The reported ^{7}Li/^{6}Li ratio suggests that 6-19% of solar lithium is produced in this way.

This spallation production of lithium appears consistent with estimates of solar-wind ^{14}C and ^{10}Be abundances, also based on lunar measurements. Using a leaching technique, the solar-wind-derived $^{14}C/H$ mixing ratio was estimated to be 2.2-3.5 x 10^{-14}, assuming a constant ratio over the last several thousand years [49]. In a similar experiment, ^{10}Be was recovered corresponding to a $^{10}Be/H$ mixing ratio of $1x10^{-14}$ [50]. Based on these radioactive isotope abundances, relative to the inferred production rates near the solar surface, essentially all of these species must be ejected in the solar wind and energetic-particle events rather than being mixed into the bulk of the OCZ. The mean residence time for spallation-produced isotopes near the surface of the sun appears, from these studies, to be at most between several hundred years and several thousand years.

Solid-forming elements from magnesium to iron. These make up the bulk of the in-situ solar-wind measurements in Table 1. The results are basically all consistent with terrestrial compositions, within the roughly 60 to 100 permil uncertainties. Attempts to measure solar-wind compositions of these elements in lunar regolith samples have been nearly all unsuccessful because the natural abundances of these elements tend to be high in lunar rocks and soils. Minerals must be used which exclude the element of interest during formation, such as using ilmenite for solar-wind Si or plagioclase for Cr. Kitts et al. [51] recently analyzed Cr from Apollo 16 plagioclase grains in search of isotope-specific anomalies (their study was not sensitive to mass-dependent fractionation departures from isotopically normal Cr). Using successive etch steps they found a surface-correlated chromium abundance enrichment corresponding to approximately 70 times that expected for solar wind, relative to argon abundances. Isotopically, a ^{54}Cr enrichment of approximately 1 permil (10 epsilon units), and an enrichment about half that at ^{53}Cr was reported, relative to planetary ^{50}Cr and ^{52}Cr. The significance and source of these isotopic anomalies, whether solar or otherwise, are unclear.

Noble gases. The solar noble gas composition is important in understanding the source and composition of the initial volatile inputs to the planets, and in understanding the history of degassing and atmospheric evolution of the planets. Spacecraft measurements made on helium, neon, and argon isotopes (Table 1 and previous discussions) are in agreement with the higher precision measurements made on the Apollo foils and on regolith samples. Krypton and xenon abundances were too low for measurement in the Apollo foils, along with $^{40}Ar/^{36}Ar$, expected to be $< 5 \times 10^{-4}$ in the sun. Planetary regoliths have yielded the most accurate compositions for neon and argon, and for krypton and xenon they are the only source of information on the solar composition.

Noble gases in planetary regoliths are characterized by two distinct surface-correlated isotopic components. The two are implanted at different depths, one corresponding to solar-wind energies and compositions, and the other corresponding to 10-100 keV/amu and characterized by enrichment of the heavy isotopes. The deeper component has been labeled the SEP (Solar Enegetic Particle) component, based on the fact that it would take more energetic particles to be implanted at the depths at which this component is found. However, the SEP abundances are orders of magnitude higher than that expected from any present-day flux of high energy solar particles. The SEP isotopic fractionation relative to solar wind is proportional to the square of the mass, so for example $(^{20}Ne/^{22}Ne)_{SEP} = (^{20}Ne/^{22}Ne)_{SW} * (20/22)^2 = (13.7) * (20/22)^2 \cong 11.3$. The abundance ratio of SEP to solar wind is nearly constant for all noble gases, in the range of 20-

30% (e.g., [52]). The SEP component is found equally in the lunar regolith and in mineral grains of solar gas-rich meteorites, so the phenomenon is not specific to one particular body. It also appears in regolith materials exposed to the sun at different points in time, so it cannot be from a particular epoch in solar history. However, SEP compositions were not measured in the Apollo SWC foils (Fig. 1), and recent interplanetary dust particle measurements [53] show a substantially reduced SEP component. As the isotopic composition can be matched simply by implanting solar-wind composition isotopes with greater energies, the suprathermal energy tail of the solar wind has been suggested as a possible source, if its intensity were substantially higher in the past [52,54]. A second recent suggestion is that the SEP component consists of interstellar pick-up ions which are ionized and accelerated in the heliosphere and subsequently implanted in regolith grains [55]. The suprathermal explanation would require some mechanism to cause much higher suprathermal fluxes in the past. The pick-up ion suggestion has an explanation for higher fluxes in that the solar system has passed through regions of significantly higher neutral particle densities in the past. However, this suggestion would constrain interstellar noble gas compositions, after fractionation by the ionization process within the heliosphere, to be isotopically and elementally very similar to solar.

The fact that there are two isotopically distinct components in regolith materials makes it more difficult to determine the pure solar wind composition. Some uncertainty remains on the composition of the end-members. Solar-wind neon from regolith samples agrees with the Apollo foil ^{20}Ne/^{22}Ne values, and has much higher precision (Table 1). But for argon there is disagreement over the solar-wind end-member composition. Palma et al. [56] report a value of ^{36}Ar/^{38}Ar = 5.80±0.06, while Benkert et al. [57] and Becker et al. [58] obtained ratios of ^{36}Ar/^{38}Ar = 5.48±0.05 and 5.58±0.03, respectively. Which ratio is correct has significant implications for planetary atmospheric evolution models. An important point is that, for the lower range of regolith values, application of solar-wind isotopic fractionation factors based on the Coulomb drag model [e.g., 7] can yield a photospheric composition identical to the terrestrial atmosphere (5.35) [59].

Data for solar-wind krypton and xenon isotopes are given in Tables 2 and 3. For krypton, the data in Table 2 are an average of 13 samples, mostly lunar ilmenite grains. Krypton isotopes show a straight fractionation trend relative to the terrestrial atmosphere of ~8 permil/amu. Plausible Coulomb drag fractionation factors can reduce the difference between photosphere and terrestrial atmosphere to between 1 and 2 permil/amu, but does not seem to remove the difference entirely. Stronger fractionation in the past, during the bulk of the lunar implantation, could possibly account for solar-wind - terrestrial differences for both Kr and Ar. The solar-wind xenon isotopic pattern is more complicated, and solar-wind fractionation cannot account for the bulk of the difference between terrestrial and solar wind Xe.

The xenon data in Table 3 are based on the initial two etch steps of a lunar ilmenite separate [60], with some modification, e.g., using data from additional samples to reduce the uncertainty for ^{124}Xe [61]. Solar-wind Xe has been interpreted as a combination of a primordial component called U-Xe, a proposed building block for the Xe found in most meteorites, the Sun, and the terrestrial atmosphere [62,63], and a heavy-isotope component contributing substantially to ^{134,136}Xe, and possibly also to ^{131}Xe. This heavy-isotope component could either be H*-Xe or the heavy-isotope portion of Xe-HL*. H*-Xe is a component consisting solely of ^{134,136}Xe [61].

Xe-HL* is found in presolar diamonds and is characterized by strong enrichments in both heavy and light isotopes. The problem with invoking addition of the heavy-isotope portion of Xe-HL* is that the heavy and light components have never been found separate from each other. At any rate, the inferred presence of U-Xe combined with variable amounts of heavy-isotope Xe in the Sun, meteorites, and the atmosphere of the Earth suggests a possible change between the time of accretion of material to the Sun and the formation of the meteorites and the terrestrial planets [63].

Prospects and Final Remarks

Solar and solar-nebula compositions have long been inferred from primitive meteorites in the absence of direct solar data. This link was most tenuous for isotopic data, where there was essentially no proof that solar isotopic compositions were the same as planetary or meteoritic compositions. The return of samples and solar-wind-irradiated foils from the Moon during the Apollo program significantly increased our isotopic understanding for certain key elements, such as for He, Ne, and Ar through the SWC experiments, and for Ar, Kr, Xe through the analysis of lunar soils. However, a relatively complete understanding of the isotopic systematics for other elements such as N and Li have only recently been obtained from lunar samples. Within the next several years we should see significant additional progress. The return of the Genesis capsule to Earth following two-plus years of solar-wind exposure, promises a wealth of information from analyses of implanted samples [64]. The primary goals of the Genesis mission address all of the issues mentioned here. Genesis will enable measurement of solar-wind isotopic compositions to unprecedented precisions, with a goal of ±1‰ for some of the most important measurements.

With the significant improvement in solar-wind isotopic precision promised by Genesis, other issues will rise in importance for interpreting the results, specifically for understanding the nebular isotopic composition. Three major issues will be a) to confirm or model accurately and with confidence the effects of gravitational separation on the composition of the OCZ, b) to characterize any isotopic fractionation in solar-wind acceleration, and c) to understand possible biases in the Genesis samples in light of the significant short-term variability reported for solar-wind helium isotope ratios. The Genesis mission attempts to address each of these issues. To characterize fractionation (b), separate samples were collected for each of the major regimes: interstream, high speed, and coronal mass ejection. The zeroth order test of isotopic fractionation is the comparison of compositions from these different regimes. No difference will suggest the absence of isotopic fractionation. Differences, if found, will be important for a better understanding of the solar-wind acceleration, and should aid in modeling this process. The models can in turn be used to estimate the isotopic compositions of the OCZ, potentially satisfying the original goal of Genesis, though the de-convolution of the fraction effects and their dependence on solar conditions could be challenging.

The issue of solar-wind variability (c) is addressed in part by the long Genesis collection times. Interstream and high-speed collectors each have more than ten months of exposure, while a continuous collector has over 850 days of exposure compared with < 2 full days exposure for the SWC foils. A number of different solar-wind parameters, including ion speed, flux, temperature, charge states, and compositions similar to those given in Table 1 from spacecraft measurements are being compiled for the Genesis collection period, and will be important for understanding the context of the Genesis samples. Additional studies of long-term variability of solar-wind isotope ratios can be carried out over other time periods. For example, SOHO and Wind have nearly completed one solar cycle of measurements with which comparisons can be made between solar maximum and minimum compositions. Finally, the issue of gravitational separation in the sun (a) will be addressed by comparisons between meteoritic and solar compositions for isotopes of heavy and light elements. Assuming the other two issues can be understood sufficiently, the precision afforded by Genesis on solar material will enable us to confirm the models for gravitational separation for the first time. Clearly each of these three issues—solar gravitational settling, isotopic fractionation during solar-wind acceleration, and possible biasing of the samples—will remain important areas of study to fully understand the solar isotopic composition.

In summary, great progress is being made in understanding the solar-wind and solar isotopic compositions. For the solar composition, fruitful areas include in-situ spacecraft solar-wind measurements, continuing studies of the solar wind implanted in lunar and asteroidal soil samples, solar spectroscopic studies, and now with the return of Genesis samples, the measurement of directly-implanted solar wind in high purity substrates. The long-sought goal of basing solar and solar-nebula isotopic ratios on actual solar composition is finally being realized.

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Table 1. Solar and solar-wind isotope ratios.

Isotope	Ratio	δ	Permil	Wind	Source	Reference	Comments
D/H	Variable,$<10^{-4}$	δD	< -400	------	Optical	1	Highest for sunspots
D/H	$< 8\text{x}10^{-6}$	δD	< -950	Mean	Lunar regolith	41	Lowest D/H measured
D/H	$< 3\text{x}10^{-6}$	δD	< -980	Mean	Lunar regolith	47	Extrapolated
^{4}He/^{3}He	2500^{+2500}_{-830}			------	Optical	4	Photospheric observation
^{4}He/^{3}He	2350±120			Mean	SWC	10	Average of SWC experiments
^{4}He/^{3}He	2190±40			Mean	Lunar regolith	57	71501 ilmenite
^{4}He/^{3}He	2050±200			Mean	ISEE-3/ICI	21	3.4 year average
^{4}He/^{3}He	1900±200			Fast	ISEE-3/ICI	21	3.4 year average
^{4}He/^{3}He	2290±200			Mean	Ulysses/SWICS	20	500 day average
^{4}He/^{3}He	2450^{+160}_{-140}			Slow	Ulysses/SWICS	25	1991-96, re-analysis
^{4}He/^{3}He	3030^{+300}_{-250}			Fast	Ulysses/SWICS	25	1991-96, re-analysis
^{4}He/^{3}He	2645^{+170}_{-150}			------		26	Extrapolated to photosphere
^{7}Li/^{6}Li	>33			------	Optical	6	Photospheric observation
^{7}Li/^{6}Li	31±4			Mean	Lunar regolith	48	Correction for spallation
^{11}B/^{10}B	3-5			Mean	Lunar regolith	48	
^{12}C/^{13}C	84±5	δ^{13}C	-60±100	------	Optical	3	Photospheric observation
		δ^{13}C	59^{+67}_{-60}	------	Optical	5	Photospheric observation
		δ^{13}C	-30 to +30	Mean	Lunar regolith	Various	Range of lunar compositions
		δ^{13}C	< -105±20	Mean	Lunar regolith	37	Solar wind as end-member
^{14}C/^{12}C	$< 4.5\text{x}10^{-10}$			Mean	Lunar regolith	49	
^{14}N/^{15}N		δ^{15}N	-250 to +190	Mean	Lunar regolith	Various	Range of lunar compositions
^{14}N/^{15}N		δ^{15}N	< -240	Mean	Lunar regolith	41	Correlation with D/H
^{15}N/^{14}N	$3.8\pm1.8 \text{ x } 10^{-3}$	δ^{15}N	30±500	Mean	SOHO/MTOF	43	Revised value
^{16}O/^{18}O	440±50	δ^{18}O	130^{+145}_{-115}	------	Optical	5	Photospheric observation
^{16}O/^{18}O	450±130	δ^{18}O	110^{+450}_{-250}	Slow	Wind/MASS	33	2.5 yrs of data
^{16}O/^{18}O	446±90	δ^{18}O	120^{+280}_{-190}	Fast	ACE/SWIMS	34	2 yrs of data
^{20}Ne/^{22}Ne	13.7±0.3	δ^{20}Ne	400±30	Mean	SWC	10	
^{20}Ne/^{22}Ne	13.8±0.1	δ^{20}Ne	410±10	Mean	Lunar ilmenite	57	
^{20}Ne/^{22}Ne	13.85±0.04	δ^{20}Ne	412±4	Mean	Combined regolith	56	Lunar, Kapoeta, & Irons
^{20}Ne/^{22}Ne	13.8±0.7	δ^{20}Ne	410±70	Mean	SOHO/MTOF	65	
^{20}Ne/^{22}Ne	13.6±0.7	δ^{20}Ne	390±70	Slow	WIND/MASS	66	2 yrs of data
^{22}Ne/^{21}Ne	30±4	δ^{21}Ne	150^{+175}_{-135}	Mean	SWC	10	
^{22}Ne/^{21}Ne	29.9±0.3	δ^{21}Ne	152±10		Combined regolith	56	Lunar, Kapoeta, & Irons
^{25}Mg/^{24}Mg	0.132±0.013	δ^{25}Mg	46±87	Slow	Wind/MASS	27	17 months of data
^{25}Mg/^{24}Mg	0.128±0.011	δ^{25}Mg	9±103	Fast	Wind/MASS	27	17 months of data
^{26}Mg/^{24}Mg	0.153±0.013	δ^{26}Mg	98±86	Slow	Wind/MASS	27	17 months of data
^{26}Mg/^{24}Mg	0.138±0.012	δ^{26}Mg	-10±93	Fast	Wind/MASS	27	17 months of data
^{25}Mg/^{24}Mg	0.1408±0.011	δ^{25}Mg	112±87	Slow	SOHO/MTOF	28	7 months of data
^{25}Mg/^{24}Mg	0.1352±0.013	δ^{25}Mg	68±103	Fast	SOHO/MTOF	28	7 months of data
^{26}Mg/^{24}Mg	0.1499±0.012	δ^{26}Mg	75±86	Slow	SOHO/MTOF	28	7 months of data
^{26}Mg/^{24}Mg	0.1416±0.013	δ^{26}Mg	16±93	Fast	SOHO/MTOF	28	7 months of data
^{24}Mg/^{26}Mg	7.7±0.12	δ^{26}Mg	-68±14	Slow	SOHO/MTOF	67	
^{24}Mg/^{26}Mg	7.1±0.14	δ^{26}Mg	10±20	Fast	SOHO/MTOF	67	
^{29}Si/^{28}Si	0.0499±0.0017	δ^{29}Si	-17±33	Slow	Wind/MASS	66	2 yrs of data
^{30}Si/^{28}Si	0.0339±0.0019	δ^{30}Si	24±58	Slow	Wind/MASS	66	2 yrs of data
^{29}Si/^{28}Si	0.0447	δ^{29}Si	-118	Mean	SOHO/MTOF	29	1.3 yrs of data
^{30}Si/^{28}Si	0.0304	δ^{30}Si	-82	Mean	SOHO/MTOF	29	1.3 yrs of data
^{34}S/^{32}S	0.043±0.006	δ^{34}S	-29±135	Fast	ACE/SWIMS	68	
^{36}Ar/^{38}Ar	5.3±0.3	δ^{38}Ar$_{36}$	9±60	Mean	SWC	69	
^{36}Ar/^{38}Ar	5.48±0.05	δ^{38}Ar$_{36}$	-23.6±8.9	Mean	Lunar regolith	57	Ilmenite grains
^{36}Ar/^{38}Ar	5.80±0.06	δ^{38}Ar$_{36}$	-78±10	Mean	Lunar regolith	56	Ilmenite grains
^{36}Ar/^{38}Ar	5.5±0.6	δ^{38}Ar$_{36}$	-27±110	Fast, mean, slow	SOHO/MTOF	70,71	3.5 yrs of data
^{40}Ca/^{42}Ca	128±47	δ^{42}Ca	165^{+700}_{-300}	Mean	SOHO/MTOF	72	1 yr of data
^{40}Ca/^{44}Ca	50±8	δ^{44}Ca	-70^{+180}_{-130}	Mean	SOHO/MTOF	72	1 yr of data
		δ^{53}Cr	+0.5	Mean	Lunar plagioclase	51	Individual isotope anomalies independent of mass fractionation
		δ^{54}Cr	+1		Lunar plagioclase	51	Same as above
^{54}Fe/^{56}Fe	0.068±0.004	δ^{54}Fe	68±63	Mean	SOHO/MTOF	73	2 yrs of data, 380-400 km/s
^{57}Fe/^{56}Fe	0.025±0.005	δ^{57}Fe	80±215	Mean	SOHO/MTOF	73	2 yrs of data, 380-400 km/s

Nearly all data are 1-σ uncertainties; [34,56] are clearly 2- σ

Table 2. Solar-wind krypton isotope ratios and δ-values (‰) relative to terrestrial air [61].

^{78}Kr	^{80}Kr	^{82}Kr	^{83}Kr	^{84}Kr	^{86}Kr
0.6365(34)	4.088(14)	20.482(54)	20.291(26)	≡100	30.24(10)
+46(6)	+32(3)	+13(3)	+8(2)	≡0	-9(3)

Values are normalized to ^{84}Kr. Two-sigma uncertainties in the last two digits are given in parentheses

Table 3. Solar-wind xenon isotope ratios and δ-values (‰) relative to terrestrial air [61], with 1-sigma uncertainties.

^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
2.948(17)	2.549(82)	51.02(54)	627.3(42)	≡100	498.0(17)	602.0(33)	220.68(90)	179.71(55)
+261(6)	+169(33)	+82(11)	-34(7)	≡0	-45(4)	-89(6)	-139(4)	-174(3)

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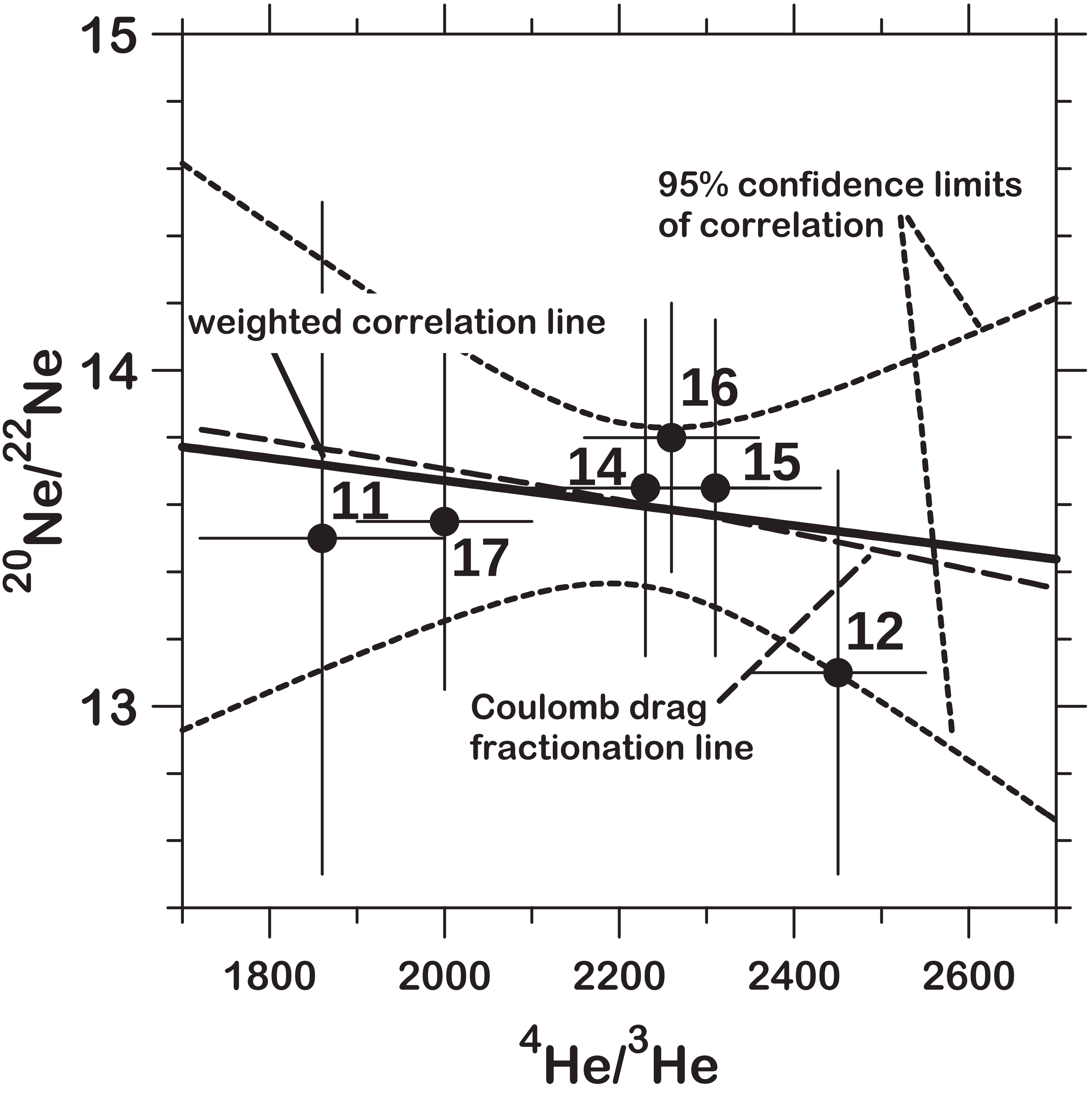
Figure 1 (below). ^{20}Ne/^{22}Ne versus ^{4}He/^{3}He from the SWC [10] and LSCRE experiments. Data points are labeled according to the respective Apollo missions during which the foils were exposed to solar wind. The Apollo 17 data point is heretofore unpublished data (F. Bühler, personal communication). A weighted correlation line is shown (solid line) with 95% confidence limits. The trend predicted by Coulomb drag fractionation theory is indicated by the dashed line.



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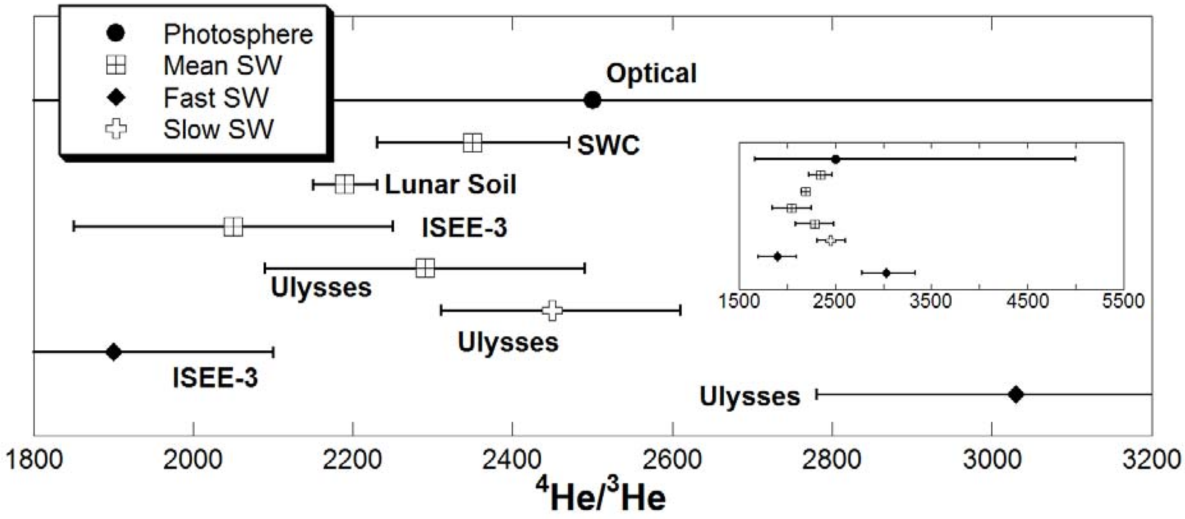

Figure 2. $^4He/^3He$ ratios reported for the photosphere and the solar wind ("SW"), from the data in Table 1.

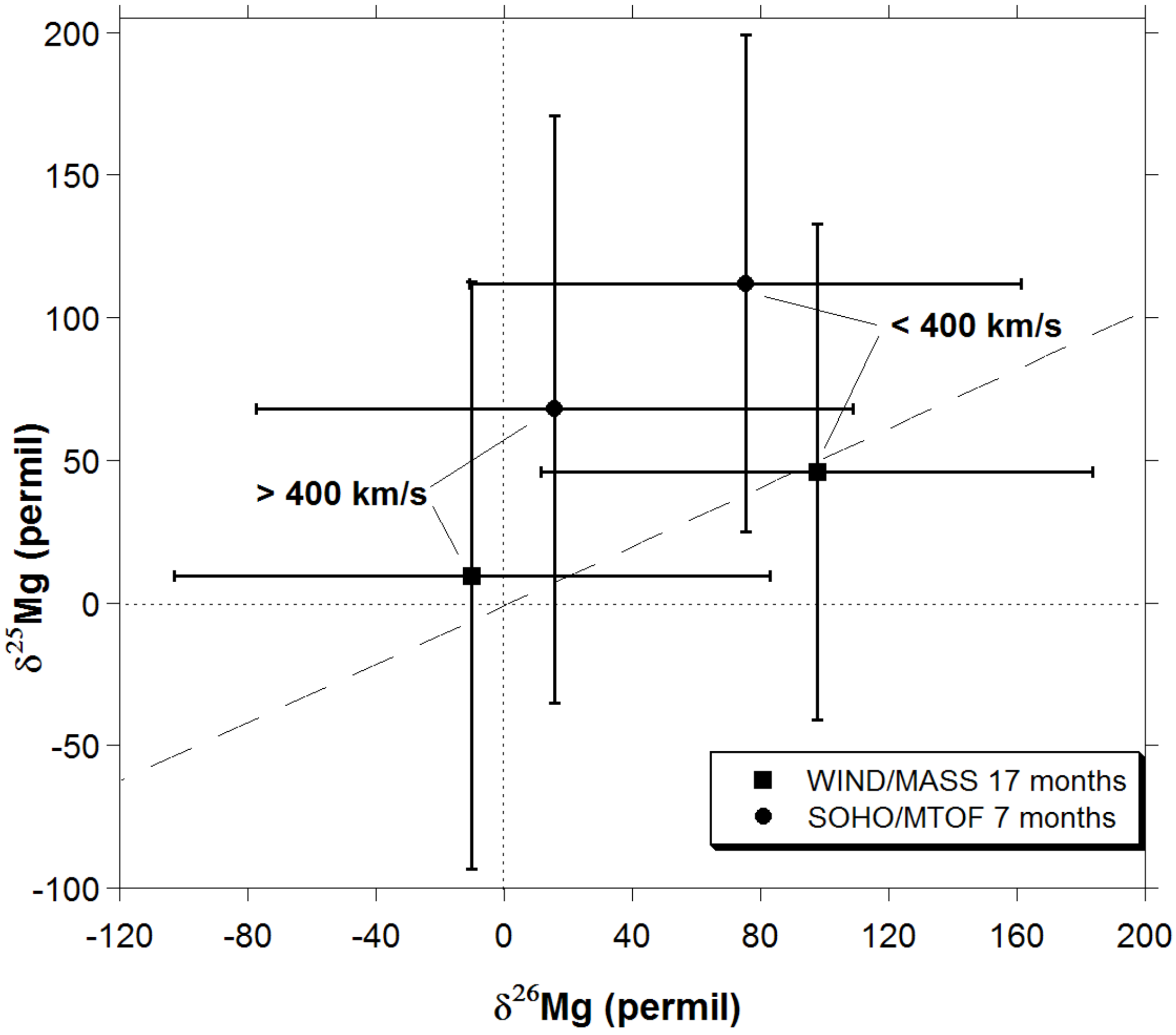

Figure 3. δ^{25}Mg vs δ^{26}Mg for in-situ solar-wind observations made by the MASS instrument on the WIND spacecraft [27] and by SOHO/MTOF [28]. The data are divided into two velocity bins, > 400 and < 400 km/s. The dashed line shows a mass-dependent-fractionation trend passing through the terrestrial composition for reference.

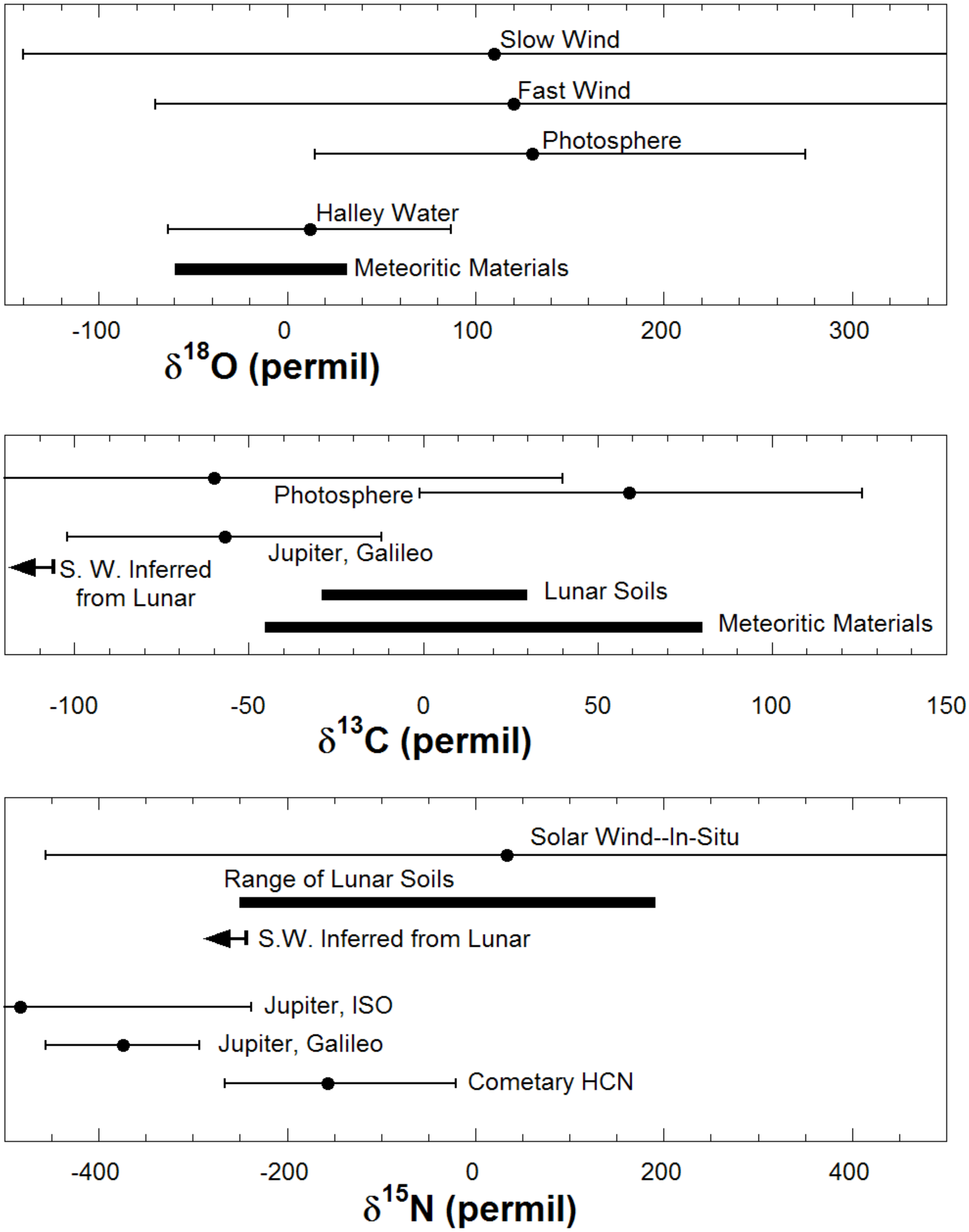

Figure 4. Isotopic compositions measured to date for the sun, solar-wind, and other relevant solar-system reservoirs. See text for explanations and references.

Biographical Sketches of the Authors

Roger Wiens began working on the Genesis mission with Don Burnett in 1990 after completing his PhD on volatiles in the Mars meteorites and in the Mars atmosphere. After seven years of working on the Genesis mission at Caltech, he moved to Los Alamos, where he led the Genesis instrument development effort there. His interests continue to include both Mars geochemistry and instrumentation, and the solar abundances that are the focus of the Genesis mission.

Peter Bochsler (below) is a professor and co-director of the Physikalisches Institut at the University of Bern. He has recently served as dean of the Faculty of Sciences. His research interests have focused on space physics, especially the acceleration and the composition of the solar wind. Professor Bochsler has been a co-investigator on a number of missions, including ISEE-3, SOHO, Wind, ACE, and Genesis.

Donald Burnett is a professor of Geochemistry at CalTech and the Principal Investigator of the Genesis Discovery Mission. His interests encompass a broad range of problems in meteoritics and planetary science. Outside of Genesis, one of his main research areas is on meteoritic Ca-Al-rich inclusions.

Robert Wimmer-Schweingruber earned his PhD at the University of Bern, Switzerland. He is currently professor at the University of Kiel, Germany, and co-director of the Institute for Experimental and Applied Physics. His interests include solar wind, suprathermal and energetic particles in the heliosphere, their composition and its relation to solar-system bodies, as well as the evolution and history of the heliosphere and solar system.