SOLAR WIND FRACTIONATION—ISOTOPIC AND ELEMENTAL—AND IMPLICATIONS FOR SOLAR COMPOSITIONS AND FUTURE GENESIS ANALYSES R.C. Wiens[1], D.B. Reisenfeld[2], V.S. Heber[3], and D.S. Burnett[4] [1]Los Alamos National Laboratory (Los Alamos, NM 87545 USA; rwiens@lanl.gov); [2]Dept. of Physics & Astronomy, U. Montana (Missoula, MT); [3]Dept. Earth and Space Sciences, UCLA (Los Angeles, CA, USA); [4]Geological & Planetary Sciences, Caltech (Pasadena, CA)

Introduction: The increasingly precise analyses of solar-wind compositions, particularly isotopic ratios obtained from GENESIS mission samples, has necessitated greater scrutiny of solar-wind elemental and isotopic fractionations during ionization and acceleration away from the Sun. For example, without a good understanding of solar-wind isotopic fractionation, the solar oxygen isotopic composition could remain imprecise at the tens of permil level even though the solar wind is measured with an order of magnitude greater accuracy [e.g., 1]. It has long been known that the solar wind is elementally fractionated. However, until a decade ago, except for a slight hint from the Apollo SWC foils [2,3], there was no evidence for long-term isotopic fractionation in the solar-wind. Evidence for isotopic fractionation between the Sun and the solar wind became stronger as a result of spacecraft observations in the late 1990s [e.g., 4-6]. But because of large uncertainties, these data were also generally consistent with no isotopic fractionation.

Light noble gas results from GENESIS samples showed clearly for the first time that isotopic ratios differ significantly between the two different types of steady-state solar wind [7], implying that bulk solar-wind is also fractionated relative to the photosphere. While we do not know *a priori* the solar isotopic composition of volatile elements, we can perhaps assume that non-volatile elements such as Mg and Si have the same isotopic composition between the Sun and the Earth. So a precise isotopic measurement of solar-wind Mg may determine the solar-wind isotopic fractionation for Mg. However, extending this isotopic fractionation to other elements with other charge states and masses requires an accurate theoretical model of solar-wind acceleration. In this presentation we review what is known about elemental fractionation between the photosphere and solar wind, isotopic fractionation between solar-wind regimes, critical measurements to further constrain these data, and implications for solar compositions based on long-standing solar-wind measurements.

Characteristics of Solar-Wind Fractionation: A theory to explain solar-wind fractionation must account for a) a ~50% lower He/H ratio in average solar wind than in the photosphere, b) a clear positive correlation between solar-wind speed and He/H ratio during solar minima [8,9], c) depletion in the solar wind of *elements* with a high first ionization time [10], d) depletion of heavy *elements* most strongly among high-FIP elements in transient coronal mass ejections (CME), and secondly in slow solar wind, relative to fast wind [7], e) depletion of heavy *isotopes* in slow solar wind, but less depletion of heavy *isotopes* in transient CMEs [7]. A qualitative picture could be constructed, at least for heavy, high FIP elements, in which material trapped in magnetic loops just above the Sun experiences collisional and gravitational-induced depletion of the heavy elements. This material is most strongly represented in transient CMEs, while slow solar wind combines some fresh photospheric material with material that has been trapped in magnetic loops by releasing it through magnetic reconnection. The fast solar wind emanating from coronal holes is thought to be most representative of the Sun both isotopically and elementally. Qualitatively it is not clear why CMEs, which seem to have the strongest elemental fractionation, have isotopic ratios in between slow and fast wind, at least in GENESIS samples [7].

Solar-Wind Fractionation Theory: A satisfactory theory for explaining these observations is significantly lacking. Well before GENESIS, measurement of solar-wind isotopic ratios were too imprecise, so until the late 1990s the theory focused solely on elemental ratios. In addition, estimates of photospheric elemental abundances have changed by more than 40% over the last twenty years (Fig. 1). Based on estimates at the time, solar-wind elemental abundances seemed to be fractionationed by a factor of 4 between low and high first ionization potential (FIP) elements [14,15]. However, this was in part due to an overestimation of high FIP elements in the photosphere. The estimated fractionation has since been reduced. Most FIT theories use a parameter of first ionization time (FIT), a more descriptive physical quantity, but one whose value depends on assumptions of the UV flux in the solar environment, the magnitudes of which could vary significantly both temporally and spatially [e.g.,16].

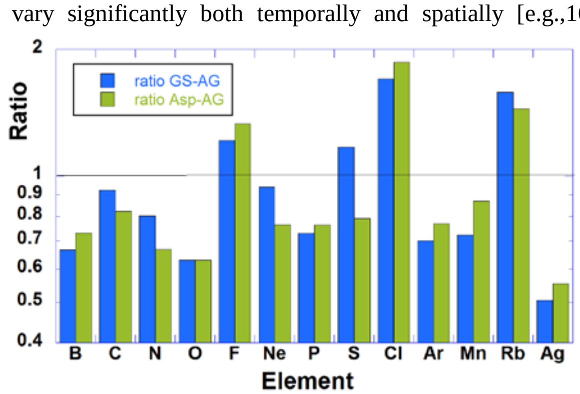

Fig. 1. Evolution of reported solar abundances derived from adsorption line strengths for selected elements. Shown are the ratios of values from Grevesse and Sauval (2002; blue) and from Asplund et al. (2009; green), both compared to values reported by Anders and Grevesse (1989) [11-13].

Regardless, it is clear that one element dominates the FIT fits: Al has a significantly lower FIT than other low-FIP elements (Fig. 2). Giammanco et al. [17] found a significantly enriched Al abundance in their slow solar wind observations and were able to fit an empirical trend relating elemental abundance to FIT values even though an earlier attempt using a larger spread of solar-wind speeds [16] had not found

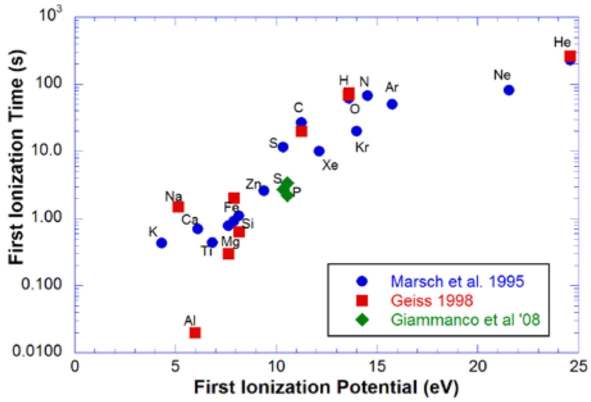

Fig. 2. Comparison of calculated first ionization times (FIT) [17,24,25] with first ionization potential (FIP). Aluminum has a unique FIT.

this effect. More study is needed to determine under what conditions the solar-wind elemental fractionation can be described by an empirical FIT fit.

Isotopic fractionation: Classical FIP/FIT theory does not result in isotopic fractionation to first order. Indeed, any isotopic fractionation that does occur must be independent of the ionization stage. Isotopic ratios are potentially affected by three processes during residence in the upper solar atmosphere and during acceleration: wave heating, gravitational settling, and Coulomb drag in which heavy ions are knocked or 'dragged' upward by collisions with protons. A basic theory of Coulomb drag has been developed [18-21]. Its application ties isotopic fractionation He/H fractionation.

If one assumes that all of the helium depletion in the solar wind is due to inefficient Coulomb drag, significant isotopic fractionations are inferred between solar wind and the photosphere, on the order of 60‰ for $^{18}O/^{16}O$, and on the order of 30‰ for $^{22}Ne/^{20}Ne$. Fractionation between interstream (slow) and coronal hole (fast) wind predicted by this model is less than observed between the GENESIS regime samples [7]. A final solar wind fractionation theory will probably invoke a combination of physical processes—ionization, gravity, Coulomb drag, and potentially also wave heating.

High-priority GENESIS measurements: To help understand isotopic fractionation, the highest priority is to precisely measure the isotopic ratios of at least one non-volatile element, such as Mg or Si. Assuming that solar composition is the same as terrestrial (except for 1-3‰/amu gravitational fractionation in the Sun [20,23]), such a measurement will provide a tie point which can be used to predict isotopic fractionation for other elements. Another important parameter is isotopic fractionation of heavy elements, such as Kr and Xe, observable in GENESIS regime samples. Likewise, to understand and constrain elemental fractionation, a precise measurement of the solar-wind Al abundance is needed to confirm the FIT fit in [17]. It may also be important to make this measurement in the slow solar-wind regime sample as well as bulk. Once solar-wind elemental fractionation is better understood, GENESIS and other solar-wind measurements may be able to constrain solar abundances more accurately than photospheric line observations.

Implications for primitive solar isotopic compositions: Applying the Coulomb drag isotopic corrections, or even slightly stronger corrections suggested by the differences in solar-wind regimes [7], to well-known solar-wind compositions, one arrives at substantially different solar isotopic compositions. If one also corrects these values for expected gravitational settling over the lifetime of the Sun [20,23], the primordial solar $^{4}He/^{3}He$ increases to > 3000, as already pointed out [e.g., 6]; $^{20}Ne/^{22}Ne$ drops to ~13.0, and primordial $^{36}Ar/^{38}Ar$ drops to ~5.32. One would expect the primitive solar composition to be recognizable elsewhere in the solar system. For argon phase Q is reasonably close (5.34 [26]). However, there appear to be no primitive Ne components with composition close to that suggested for primitive solar composition, the closest being Ne-B ($^{20}Ne/^{22}Ne$ = 12.5 [22]), except for the possibility of the jovian atmosphere, which is not measured accurately for Ne isotopes.

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