

**MEASURING SOLAR WIND C AND O ABUNDANCES IN GENESIS REGIME COLLECTORS USING SIMS ION IMAGING DEPTH PROFILING.** K. D. Rieck<sup>1</sup>, R. C. Ogliore<sup>2</sup>, A. J. G. Jurewicz<sup>3,4</sup>, D. S. Burnett<sup>5</sup>, Y. Guan<sup>5</sup>, and R. C. Wiens<sup>1</sup>, <sup>1</sup>Los Alamos National Laboratory, ISR-2, MS-D434, SM-30, Bikini Atoll Rd., Los Alamos, NM 87545, USA; kdriec@lanl.gov, <sup>2</sup>Washington University in St. Louis, Phys., St. Louis, MO, USA, <sup>3</sup>Arizona State University, SESE, CMS, Tempe, AZ, USA, <sup>4</sup>Dartmouth College, Earth Sci., Hanover, NH, USA, <sup>5</sup>Caltech, Geo. & Pl. Sci., Pasadena, CA, USA.

**Introduction:** Samples of solar wind (SW) were returned to Earth for analysis by the Genesis spacecraft so that SW could be used to provide accurate and precise measurements of solar composition [1]. However, elemental and isotopic fractionation due to SW formation changes the composition of the SW relative to photospheric abundances [e.g., 2, 3]. This fractionation ( $F_{\text{sw-phot}}$ ) must be quantified (and subtracted from SW composition) to derive accurate solar data from SW.

To model  $F_{\text{sw-phot}}$  solar physicists need to understand the physics behind the processes underlying SW formation and acceleration.  $F_{\text{sw-phot}}$  is primarily related to each element's first ionization potential (FIP), but secondary factors (e.g., an ion's atomic mass and velocity) also affect fractionation [3]. Laming *et al.* [4] proposed models (constrained by Genesis-derived data) based on SW formation driven by ponderomotive forces in the solar corona and further fractionation through conservation of energy (1<sup>st</sup> adiabatic variant) during acceleration away from the Sun. These models successfully model the component of  $F_{\text{sw-phot}}$  due to FIP [5].

Our goal is to test the mass-dependent component of the models of [4] and to provide data on the mass dependence of  $F_{\text{sw-phot}}$  for elements. We focus on analyzing carbon, nitrogen, and oxygen (CNO) fluences in the bulk SW (B/C array) and three SW regimes returned by Genesis [1]: high speed SW (H array = "coronal hole" >500 km/s), low speed SW (L array = "interstream" <500 km/s), and coronal mass ejections (E array).

**Why CNO?:** (a) CNO are the lowest mass minor SW elements currently analyzable by SIMS in Genesis samples (helium does not behave like a minor element). (b) CNO have FIPs in the range 11 to 15eV; i.e., they bridge the transition between low-FIP and high-FIP fractionations -- key for testing theory -- and (c) their FIP is the highest for which photospheric absorption lines exist. Deviation from photospheric abundances can indicate fractionation.

**Techniques:** Although "abundant" in the SW, there are only  $1 \times 10^{12}$  to  $2 \times 10^{13}$  ions  $\text{cm}^{-2}$  (each) of  $^{12}\text{C}$ ,  $^{14}\text{N}$ , and  $^{16}\text{O}$  in Genesis bulk SW collectors [6] and  $\sim 1/3$  to  $1/4$  that fluence predicted in each of the regime collectors. Moreover, CNO are the major components of our atmosphere. It is critically important to obtain accurate measurements of the peaks of the SW implant just  $\sim 30$  to 80 nm from the collector surface (indeed, closer to

the collector surface is better) without integrating signal from surface contaminants. This requires novel sample preparation and analysis techniques. Details of previous sample-preparation tests are given in [7], with an overview below. Here, the technique of ion imaging depth profiling [8] by secondary ion mass spectrometry (SIMS) is used to measure CNO solar material only nanometers from the collection surfaces of the flight wafers. Ion imaging allows for pixel-by-pixel depth correction and elimination of pixels that are contaminated by terrestrial particulates (Fig. 1) and analytical artifacts.

**Samples and Preparation:** Genesis samples are float-zone (FZ) silicon  $\sim 4$  to 6 mm in diameter (B/C: #61164, H: #61409, L: #61386, E: #61395). Flight-spare Genesis FZ silicon was used in implant standards.

These were prepared for SIMS as per the best results from [7]. That is, each Genesis wafer was cleaned using xylenes, acetone, methanol, ultra-pure water (UPW), and dilute hydrofluoric acid (1:100, 49% HF:UPW), which are particularly effective for removing terrestrial C without adding O). Then, the freshly cleaned wafer surfaces were partially protected with Si film using electron-beam physical vapor deposition. Although applying the thin film of Si did not offer the hoped for protection from environmental C, N, or O, the brief drop in Si count rate intensity at the wafer-film interface during depth profiling served as a precise depth marker for making topographic corrections to ion imaging data. Then, all samples were mounted (front side down) and polished (from the back side) by EAG Laboratories. This is now common practice for preparing Genesis wafers for analysis as it reduces interference from surface contaminants (e.g., [9]). The collector wafers were polished to a thickness of  $\sim 800$  nm. After polishing, all samples were implanted by Leonard Kroko, Inc. with a nominal dose of  $1 \times 10^{13}$  atoms  $\text{cm}^{-2}$  (each)  $^{13}\text{C}$ ,  $^{15}\text{N}$ , and  $^{18}\text{O}$  (75 keV). External standards (C: LANL 5-05\_13C, O: K 09-07\_18O15N, [9]) were used to calibrate the implant fluences, and in turn the implanted ions were used to calibrate our  $^{12}\text{C}$ ,  $^{14}\text{N}$ , and  $^{16}\text{O}$  measurements. Implanting minor isotopes allows us to easily distinguish reference ions from most terrestrial contaminants, and SW profiles, which are primarily composed of major isotopes.

**C and O measurement:** Depth profiling was performed using the Cameca ims 7f-Geo SIMS at Caltech.

A rastered 10 keV Cs<sup>+</sup> primary beam (~0.2 to 0.3 nA; spot size ~5 μm) was used (sample potential = -9 keV; impact energy = 19 keV; raster = 50 μm, except for <sup>12</sup>C B/C = 85 μm, <sup>12</sup>C L = 75 μm, <sup>16</sup>O B/C = 100 μm). Analyses required 5 to 21 hrs, depending on raster size and sputter rate. There were no major interferences observed for either the reference species (<sup>13</sup>C, <sup>18</sup>O) or the SW species (<sup>12</sup>C, <sup>16</sup>O), so most measurements were made using a low mass resolving power of ~500 to maximize signal. Prior to measurement, the SIMS was baked for 48+ hrs. to reduce background levels of C and O. Intermittent use of blank Si sputtering, and the sublimation pump continued to keep background levels low during the session.

**Results:** Fig. 2 shows our <sup>12</sup>C profiles from B/C, L, and H arrays. The absolute <sup>12</sup>C fluence measured for B/C is  $(8 \pm 1) \times 10^{12}$  atoms cm<sup>-2</sup> (2σ). L and H fluences presented here are calculated relative to the nominal fluence ( $1 \times 10^{13}$  <sup>13</sup>C cm<sup>-2</sup>) of an internal reference implant. SW <sup>12</sup>C fluences measured in L- and H- arrays are  $(4.0 \pm 0.8) \times 10^{11}$  ions cm<sup>-2</sup> (2σ) and  $(1.2 \pm 0.5) \times 10^{12}$  ions cm<sup>-2</sup> (2σ), respectively. We expect to have the absolute implant fluences (usually ± 20% of nominal) at the meeting. Errors are calculated using a bootstrap technique of sampling the pixel data, giving a robust estimate of the total error (systematic + statistical). The bootstrap approach can only be performed with imaging data, and is a much more robust estimate than counting statistics.

**Discussion:** The bulk SW <sup>12</sup>C measurement by [6] lies within the 2σ error of our measurement. Our bulk SW C/Mg ((bulk SW Mg =  $1.66 \pm 0.07$  (1σ)) × 10<sup>12</sup> [5]) is ~70% of the photospheric abundance [10]. Relative to our B/C array result, our preliminary <sup>12</sup>C fluences measured in L- and H-arrays are lower than what would be predicted from only the relative exposure durations (B/C: 852.83 d, L: 333.67 d, H: 313.01 d [11]), (6× and 2× lower, respectively). Although the L and H reference is not calibrated, the relative fluences are precise.

**Summary and Conclusions:** We measure an absolute bulk <sup>12</sup>C flux of  $\sim 1 \times 10^5$  ions cm<sup>-2</sup> s<sup>-1</sup>. Our preliminary L- and H-array <sup>12</sup>C fluxes are  $1.4 \times 10^4$  ions cm<sup>-2</sup> s<sup>-1</sup>, and  $4.4 \times 10^4$  ions cm<sup>-2</sup> s<sup>-1</sup>.

At present, our O analyses are still being processed and will be presented at the conference. N measurements are planned for future work.

With ion imaging, contamination and other systematic ion probe errors can be identified, and affected cycles and pixels excluded from signal integration. Traditional “one-pixel” measurements likely include contamination and analytical artifacts, but they are hidden and cannot be removed. Errors calculated using the bootstrap approach are robust total uncertainties, and are

conservative estimates. Moreover, using ion imaging provides uncontaminated SW data between the collector surface and the SW peak.

Fig. 1. Ion image of a contaminant particle (yellow; raster = 85μm). Contaminants, characterized by localized elevated ion intensity, can be identified with ion imaging and excluded from the SW integration.

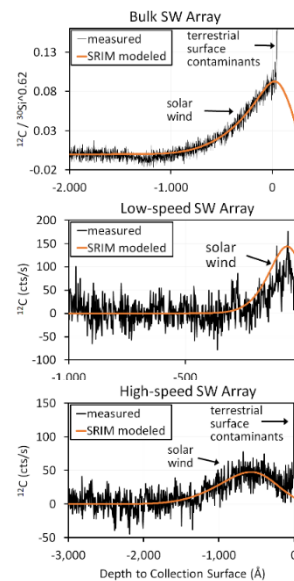
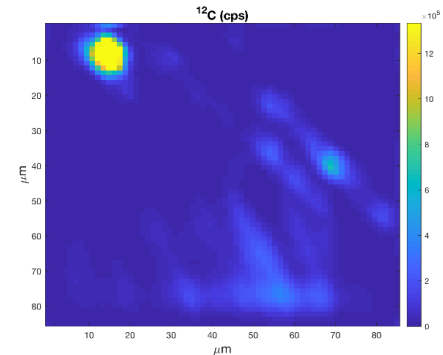


Fig. 2. <sup>12</sup>C profiles (black lines, background removed), from ion image data collected during SIMS back-side depth profiling of Genesis collectors. Scaled SRIM models (thick orange lines) are overlain for reference. The Si break through points are at 0 Å. Note: the y-axis scale for the bulk measurement includes a gamma correction.

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**References:** [1] Burnett D. S. (2013) *Meteoritics & Planet. Sci.*, 48, 2351–2370. [2] Heber V. S. et al. (2012) *ApJ*, 759:121, 1-13. [3] Pilleri P. et al. (2015) *ApJ*, 812:1, 1-10. [4] Laming et al. (2017) *ApJL*, 851:L12, 1-6. [5] Burnett D. S. et al. (2017) *LPS* 48, Abstract #1532. [6] Heber V. S. et al. (2013) *LPS* 44, Abstract #2540. [7] Rieck et al. (2018) *LPS* 49, Abstract #2875. [8] Westphal A. J. (2014) *LPS* 45, Abstract #2671. [9] Heber V. S. et al. (2014) *Chem. Geo.*, 390, 61-73. [10] Asplund et al. (2009) *Annu. Rev. Astron. Astrophys.* 47, 481–522. [11] Reisenfeld et al. (2013) *Space Sci. Rev.* 175, 125–164.