A NEW UPPER LIMIT ON THE D/H RATIO IN THE SOLAR WIND.

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Introduction: The deuterium (D) abundance in the Sun provides a direct test of our understanding of solar structure and nuclear burning history as well as a probe of spallation processes at the Sun's surface. According to standard models, the original inventory of D in the Sun was converted to ^{3}He as nuclear burning began, while the protosun was still fully convective [1]. The ^{3}He/^{4}He ratio currently inferred for the Sun is consistent with near-complete conversion of D to ^{3}He. Today, spallation reactions in the outer layers of the Sun produce D. Solar D has been observed in solar energetic particles, but not so far in normal solar wind [2]. Deuterium produced by spallation is converted to ^{3}He at the base of the Sun's outer convective zone. However, there is insufficient data to constrain the efficiency of D production and the steady-state abundance of D in the Sun's outer layers.

The only sample-based data on D/H in the solar wind come from lunar samples. Ion probe measurements of a lunar regolith sample gave δD as low as -950‰ (D/H ≈ 8×10^{-6}) [3]. Extrapolation of a correlation between δD of H_2 and mole fraction of H in H_2O gives δD for the solar wind of <-980‰ (D/H < 3×10^{-6}) [4, 5]. But these values have large uncertainties.

Although the Genesis Mission did not specifically propose to measure D/H in the solar wind, the high concentration of solar wind hydrogen in the Genesis array collectors allows us to improve the estimate of D/H in the Sun. We therefore used the Cameca ims 1280 at the University of Hawai‘i to measure D/H in diamond-like carbon on silicon (DOS) and silicon (Si) collectors from the B/C-array, which sampled the bulk solar wind, and a DOS collector from the H-array, which sampled only the "fast" solar wind [6].

Experimental: Standard implants for H (DOS, Si) and Genesis collectors 60628 (DOS, B/C-array), 60631 (DOS, H-array), and 60442 (Si, B/C-array) were mounted together in a single 9-place holder and pumped down in the ion probe airlock for three days before the analysis session. The Ti sublimation pump gettered H in the sample chamber for 24 hours prior to the session. A liquid nitrogen trap used during the measurements further reduced the sample-chamber pressure during measurements to ~1×10^{-10} torr.

A Cs$^+$ primary ion beam generated negative secondary ions of H and D. On DOS, $^{12}C^-$, $^{12}CH^-$, and $^{12}C_2$ were also monitored to help identify and constrain instrument fractionation. Before each measurement, the electron gun (~20 eV of impact energy) was used to desorb terrestrial H and D from the sample surface. To find areas clear of H hot spots, raster ion imaging of 500×500 µm areas with a primary beam of ~0.5 nA was used for 1-2 minutes. This very gentle pre-sputtering also removed some surface contamination. Data were collected by rastering a 0.5-2 nA beam over a 100×100 µm area without using the electron gun. Electronic gating was used to accept signal from the central 25-50% of the rastered area, excluding H and D from the edges of the crater or creeping along the surface into the crater. A field aperture of ~50 µm on the image plane was used in conjunction with DTOS to minimize the contribution of ions generated in the gas above the sample. Data were corrected for the duty cycle of the electronic gate and for dead time, and the H signal was time-interpolated to match the acquisition time of D.

Results: Figure 1 shows count-rate profiles for D and H in the B/C-array DOS collector. The figure illustrates several things. First, there is a baseline level of H and D in the collectors that probably represents a combination of intrinsic terrestrial hydrogen incorporated into the detector during its manufacture and a steady-state concentration of hydrogen traveling across the surface and reaching the center of the rastered area. Second, there is surface contamination that decreases rapidly but also has a tail that continues to contribute over the first ~25 minutes of a measurement, overlapping the solar wind profile. This contamination is reduced by a factor of ~100 by using the electron gun to degas the surface, but the surface contamination cannot be totally eliminated. Third, there is a transient period at the beginning of the measurement during which the production of secondary ions starts out very low and grows to its steady-state value. This transient period also affects the measurement of the solar wind profile.

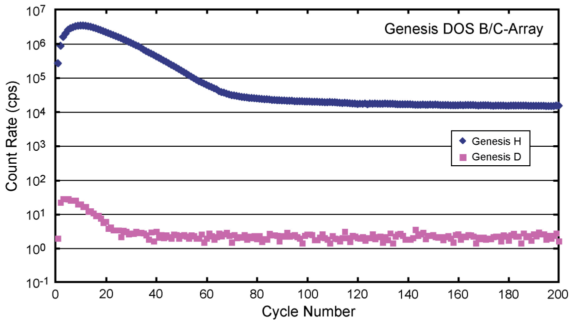

Figure 1: Count-rate profiles for Genesis DOS B/C-array.

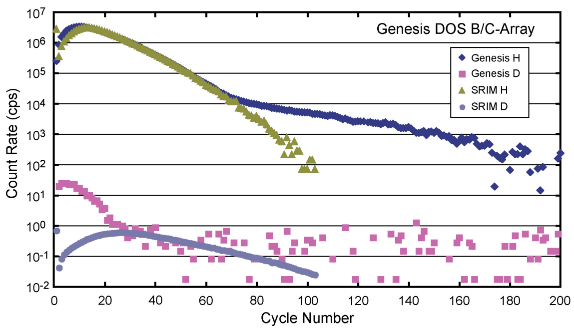

Figure 2: Background-corrected count-rate profiles for the Genesis DOS B/C-array collector compared to H and D profiles calculated by SRIM. Vertical positions of SRIM profiles are adjusted to match the measured H profile and the maximum amount of D permitted by the measurement.

Three different methods were used to estimate D/H in the solar wind (Table 1). The first method is to divide the measured D count rate by the measured H count rate for each measurement cycle. The blue symbols in Fig. 3 show the D/H ratios by cycle for the measurement shown in Fig. 1. An average of the lowest ratios calculated from these data, which by chance occur at the depth where the simulated D profile peaks, is 2.0×10^{-6}. In the second method, we subtract from the measured data an average value for the baseline H and D below the implant (background-corrected profiles shown in Fig. 2). The pink symbols in Fig. 3 show ratios calculated from the background-corrected data. The average low ratio calculated from these data is 6.6×10^{-7}. The third method uses SRIM profiles calculated for the appropriate collector material and the solar wind energy distribution. Figure 2 overlays the SRIM profiles for H and D in DOS onto the background-corrected profiles. The H profile is scaled vertically to match the measured H profile, and the D profile is scaled to give the maximum solar wind D consistent with the measured profile. Note that the D profile is deeper than the H profile. The D/H ratio is estimated by integrating the scaled SRIM profiles. For the profile in Fig. 2, the upper limit for D/H in the solar wind is 3.9×10^{-7}.

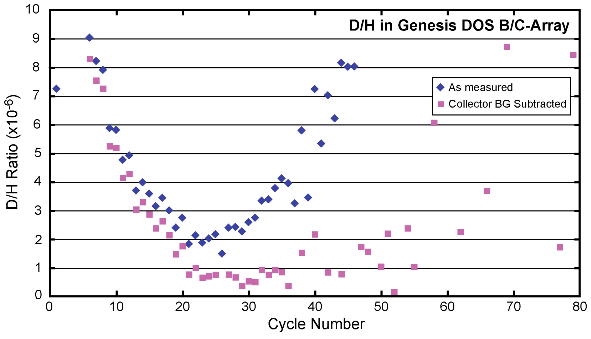

Figure 3: D/H ratios by cycle calculated from the "raw" count rates compared to the ratios calculated from data corrected for background H in the DOS B/C-array collector.

The H array has a deeper solar wind implant, so we hoped to get a better separation between the solar wind profile and the surface contamination. But the ratio of solar wind to the hydrogen background intrinsic to the collector material was significantly lower than for the B/C array, and the resulting D/H estimates were higher (Table 1). The background H and D in the B/C array Si collector are factor of 2-3 lower than in the DOS collector. The higher signal-to-noise ratio resulted in lower estimated D/H ratios for the B/C-array Si detector than for the other detectors (Table 1).

Table 1: Estimated upper limits for D/H in SW from three samples using three data-reduction techniques.

Detector	"Raw data"	BG corr data	SRIM profile
DOS B/C	2.0×10^{-6}	6.6×10^{-7}	3.9×10^{-7}
DOS H	1.1×10^{-5}	1.1×10^{-6}	9.7×10^{-7}
Si B/C	4.5×10^{-7}	2.3×10^{-7}	2.0×10^{-7}

Discussion: All D/H values inferred from the B/C array collectors (Table 1) are significantly lower than previous estimates from lunar soils (3-7×10^{-6} [4, 5]). It is likely that the true ratio in the average solar wind and the solar photosphere is even lower. Our upper limits on D/H scale with background hydrogen (signal to noise) measured in the collector. This means we are probably not seeing solar wind D. If this is true, then the best estimate comes from the Si B/C collector and D/H in the bulk solar wind is likely ≤~2×10^{-7}. There was some concern that the Si collector may have lost hydrogen via diffusion due to the high temperatures experienced during the mission. If so, then the true solar wind D/H ratio would be even lower, because diffusive loss of H should be greater than that of D.

It may be possible to get a better limit on the D/H ratio in bulk solar wind from the concentrator targets. The concentrator was designed to reject H, but should have collected more D than the passive arrays, giving us better sensitivity. Only ~1 cm of Si, which has the lowest intrinsic background, was exposed in the concentrator and it has not yet been allocated. Measuring a collector from the back side would eliminate the transient sputtering regime and surface contamination from the leading edge of the solar wind profile.

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