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THE GENESIS MISSION: SOLAR WIND CONDITIONS, AND IMPLICATIONS FOR THE FIP FRACTIONATION OF THE SOLAR WIND

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ABSTRACT/INTRODUCTION

The NASA Genesis mission collected solar wind on ultrapure materials between November 30, 2001 and April 1, 2004. The samples were returned to Earth September 8, 2004. Despite the hard landing that resulted from a failure of the avionics to deploy the parachute, many samples were returned in a condition that will permit analyses. Sample analyses of these samples should give a far better understanding of the solar elemental and isotopic composition (Burnett *et al.* 2003). Further, the photospheric composition is thought to be representative of the solar nebula, so that the Genesis mission will provide a new baseline for the average solar nebula composition with which to compare present-day compositions of planets, meteorites, and asteroids. Sample analysis is currently underway.

The Genesis samples must be placed in the context of the solar and solar wind conditions under which they were collected. Solar wind is fractionated from the photosphere by the forces that accelerate the ions off of the Sun. This fractionation appears to be ordered by the first ionization potential (FIP) of the elements, with the tendency for low-FIP elements to be over-abundant in the solar wind relative to the photosphere, and high-FIP elements to be under-abundant (e.g. Geiss, 1982; von Steiger *et al*., 2000). In addition, the extent of elemental fractionation differs across different solar-wind regimes. Therefore, Genesis collected solar wind samples sorted into three regimes: 'fast wind' or 'coronal hole' (CH), 'slow wind' or 'interstream' (IS), and 'coronal mass ejection' (CME). To carry this out, plasma ion and electron spectrometers (Barraclough *et al*., 2003) continuously monitored the solar wind proton density, velocity, temperature, the alpha/proton ratio, and angular distribution of suprathermal electrons, and those parameters were in turn used in a rule-based algorithm that assigned the most probable solar wind regime (Neugebauer *et al.,* 2003). At any given time, only one of three regime-specific collectors (CH, IS, or CME) was exposed to the solar wind.

Here we report on the regime-specific solar wind conditions from *in-situ* instruments over the course of the collection period. Further, we use composition data from the SWICS (Solar Wind Ion Composition Spectrometer) instrument on ACE (McComas *et al*., 1998) to examine the FIP fractionation between solar wind regimes, and make a preliminary comparison of these to the FIP analysis of Ulysses/SWICS composition data (von Steiger *et al.* 2000).

Our elemental fractionation study includes a re-evaluation of the Ulysses FIP analysis in light of newly reported photospheric abundance data (Asplund, Grevesse & Sauval, 2005). The new abundance data indicate a metallicity (Z/X) for the Sun almost a factor of two lower than that reported in the widely used compilation of Anders & Grevesse (1989). The new photospheric abundances suggest a lower degree of solar wind fractionation than previously reported by von Steiger *et al.* (2000) for the first Ulysses polar orbit (1991-1998).

1. SOLAR WIND CONDITIONS DURING GENESIS MISSION

The Genesis sample collection period began near the peak of Solar Maximum and proceeded for 28 months (852.83 days). Fig.1 shows a histogram of the solar wind velocity distribution during the collection period, coded by solar wind regime as defined by the on-board algorithm. During the sample collection period, the exposure time for the regime-specific collector was as follows: the IS collector was deployed for 39.1 % of the time, the CH collector for 36.7 % of the time, and the CME collector for 22.7 % of the time. The remaining time (1.5%) the collectors were stowed, typically for spacecraft maneuvers. Note the time for deployment of the CME collector (22.7%) is much higher than the observed single-point observation time fraction of CMEs, 15% at Solar Maximum, and < 1% at Solar Minimum (Gosling *et al*., 1992). This is because the algorithm requires that the CME collector be deployed for a minimum of 24 hours, which was done to prevent contamination of the IS and CH collectors by CME material, whereas the average CME duration is

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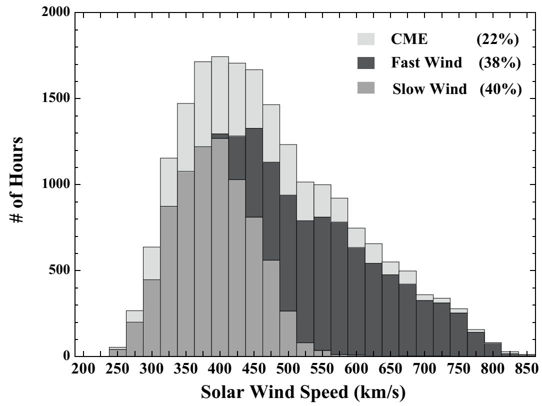

Figure 1. Distribution of solar wind velocities during Genesis sample collection period, designated by solar wind regime as determined by on-board algorithm.

~18 hours. The number of times the algorithm triggered the deployment of the CME collector was 106, corresponding to a CME *occurrence rate* of 44 events yr^{-1}. As the collection period was during the waning phase of the solar cycle, this compares favorably to the rates reported by Gosling *et al*., (1992) of 72 CMEs yr^{-1} during solar activity maximum and 8 CMEs yr^{-1} at minimum.

2. COMPARISONS TO *IN SITU* ELEMENTAL ABUNDANCE MEASUREMENTS

The purpose of the Genesis mission is to determine the isotopic and elemental abundances of the protosolar nebula. The photosphere is expected to have a composition almost identical to the protosolar nebula, but it well established that the solar wind composition differs from the photosphere, and the composition varies with solar wind regime. Thus, in order to achieve the fundamental goal of Genesis, we must understand the quantitative relationship between the solar wind composition and the photospheric composition. This motivates the need for regime-specific samples, as we hope to use knowledge of the variation between regimes to help us establish the connection between solar wind and photospheric composition.

Ultimately sample analysis should reveal with unprecedented accuracy isotopic and elemental abundances of specific solar wind regimes. However, the abundance values are averages for the entire collection period; no temporal information extists. It will be important to connect the Genesis abundances to coeval as well as earlier time-resolved measurements, as this will determine how representative the Genesis sample is of the solar wind over time.

2.1. Comparison to ACE measurements

Genesis does not have instruments capable of performing time-resolved heavy-ion composition measurements; thus, to address this issue, we turn to the Solar Wind Ion Composition Spectrometer (SWICS) on board the Advanced Composition Explorer (ACE) (Gloeckler *et al.* 1995) to provide composition information that we can then correlate with the Genesis data. At the present time, only the Mg/O (low-FIP) and Ne/O (high-FIP) elemental ratios are available. As more ACE data becomes available, we will expand the present study to include additional elemental ratios.

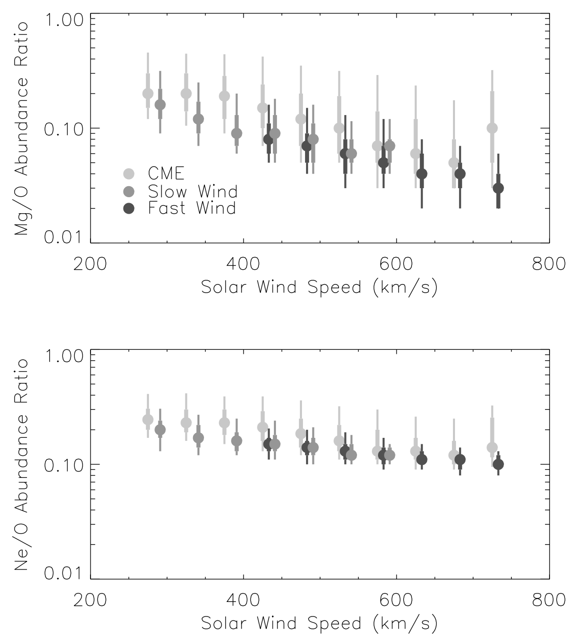

Figure 2. ACE Mg/O (upper) and Ne/O (lower) elemental ratios vs. solar wind speed, for the three solar wind regimes over the course of the Genesis sample collection period. Data is binned into 50 km/s intervals. Within each interval, the solid circles represent the median value of the distributions; the thick bars span the 25- to 75-percentiles; the thin bars span the 10- to 90-percentiles.

In Fig. 2 we show ACE/SWICS elemental abundance data for the Mg/O and Ne/O ratios binned by solar wind proton speed and sorted by Genesis regime selection. There is clearly a speed-dependent variation, with both the Mg/O and the Ne/O ratios decreasing from slow to fast. The variation for Mg/O is the largest, dropping by a factor of ~5 from 275 to 775 km s^{-1}. The Ne/O ratio also drops significantly, by a factor of 2 across the same speed range. The average values within each regime are, for Mg/O, 0.12 for the slow wind and 0.068 for the fast wind. For Ne/O, the averages are 0.18 for the slow wind, and 0.13 for the fast wind. It has been observed recently by Richardson & Cane (2004) that an even stronger correlation exists between elemental abundance and freezing in tempature as exhibited by the O^{7+}/O^{6+} charge state ratio, which generally anti-correlates with speed. Fig. 2 also demonstrates that CME material consistently exhibits Mg/O and Ne/O ratios higher than either fast or slow slow wind for a given speed, a point first made by Reisenfeld (2003) and further elaborated by Richardson & Cane (2004). The average values for the CME regime are 0.22 for Mg/O and 0.24 for Ne/O.

We note that at this time, only relative differences between regimes and species should be considered. The absolute scale of the ACE abundances should be considered preliminary, as the ACE /SWICS absolute calibration is still in progress.

2.2 Re-analysis of Ulysses Elemental Abundances

Before comparing the ACE elemental abundance measurements for the Genesis regime times to the Ulysses measurements, we will re-evaluate the results of von Steiger *et al.* (2000) in light of a new photospheric abundance analysis by Asplund, Grevesse & Sauval (2005), which supersedes the compilation of Grevesse & Sauval (1998) used by von Steiger *et al*.

The latest photospheric abundances are based on time-dependent, 3-D hydrodynamical model of the solar atmosphere instead of a 1D hydrostatic model that formed the basis of the Grevesse & Sauval (1998) abundances. As a result, simulated 3D line profiles now agree almost perfectly with observed spectral features, and for the first time, abundances calculated using atomic and molecular lines are in agreement. Significant abundance shifts for relevant FIP species include a ~30% drop in the abundances of O, S, and N, a 42% drop in Ne, and a 26% drop in C.

The effect of these shifts on the FIP analysis presented by von Steiger et al. (2000) is shown in Fig. 3 for the slow wind. The fast wind shows a similar shift. Low-FIP elements show a 25-33% drop in FIP enhancement and the solar wind to photospheric ratio of the high-FIP elements Ne and He now reverse order such that

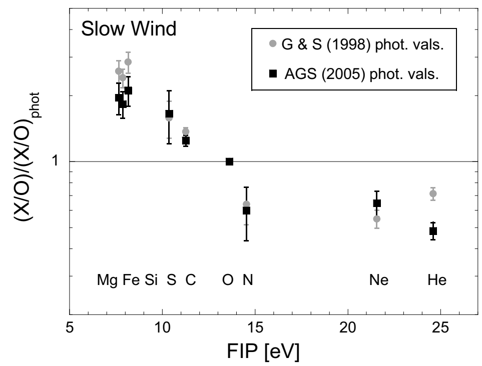

Figure 3. Average element abundance ratios relative to oxygen from Ulysses/SWICS for the slow solar wind. The ratios are divided by the photospheric ratio and plotted as a function of the first ionization potential (FIP). Plotted are abundance ratios relative to the photospheric ratios reported in Grevesse & Sauval (1998) [GS], and Asplund, Grevesse & Sauval (2005) [AGS]. The error bars span the 1-σ variation of their range. The fast wind shows a similar shift.

Ne is higher than He, resulting in a more monotonic trend as a function of FIP. To parameterize the overall effect of the new photospheric abundances, we make use of the FIP enhancement factor, which is the ratio of low- to high-FIP elements:

$$f = \frac{\left(\frac{[\mathrm{Mg}]+[\mathrm{Si}]+[\mathrm{S}]+[\mathrm{Fe}]}{[\mathrm{C}]+[\mathrm{N}]+[\mathrm{O}]+[\mathrm{Ne}]}\right)_{\mathrm{SW}}}{\left(\frac{[\mathrm{Mg}]+[\mathrm{Si}]+[\mathrm{S}]+[\mathrm{Fe}]}{[\mathrm{C}]+[\mathrm{N}]+[\mathrm{O}]+[\mathrm{Ne}]}\right)_{\mathrm{Ph}}},$$

where square brackets around element symbols denote elemental abundances. This factor, for the slow and fast wind, and as applied to the Ulysses abundance measurements relative to different photospheric values is enumerated in Table 1. Although the FIP enhancement is still present, it is significantly smaller. To highlight an historical trend, we have also included values of *f* based on the older (but still widely used) compiliation of Anders and Grevesse (1989). Clearly, as compared to earlier reports on the FIP enhancement in the solar wind, the trend shows an ever-diminishing average FIP variation relative to the solar atmosphere. This is very good news for Genesis, because if the solar wind abundance ratios are more representative of photospheric values, then relating the Genesis solar wind samples and proto-solar abundances will be somewhat more straightforward. Note, however, von Steiger *et al.* (2000) did not make any attempt to remove coronal hole associated wind from their slow solar wind sample. One should therefore expect a mixture of fast and slow wind for their "Min", and "Max" time-periods.

Table 1. FIP enhancement factors (*f*) for the slow and fast wind from Ulysses/SWICS, for different photospheric values.

	AGS (2005)	GS (1998)	AG (1989)
Slow	1.9	2.4	3.0
Fast	1.4	1.8	2.2

2.3 Comparison of ACE and Ulysses elemental abundances

We now compare the revised Ulysses Mg/O and Ne/O elemental ratios for Ulysses to those for ACE. Fig. 4 shows these ratios relative to the solar surface ratios for the fast and slow wind. As described in Section 2.1, ACE fast and slow wind periods are those determined by the Genesis onboard regime selection algorithm. We reiterate that ACE absolute abundance values should be considered preliminary. However, ACE relative differences (between fast and slow and between Mg and Ne) may be taken as meaningful. We point out the following: (1) The ratio of fractionation between Mg and Ne is significantly less for ACE than Ulysses. For the fast wind, the fractionation of Mg compared to Ne differs by a factor of 0.85 (ACE) vs. 2.6 (Ulysses). For the slow wind, the fractionation of Mg is greater than Ne by a factor of 1.27 (ACE) vs. 3.03 (Ulysses). (2) For a given element, the ratio of slow-to-fast wind fractionation is greater for ACE than Ulysses. For Mg it is 2.0 (ACE) vs. 1.36 (Ulysses), and for Ne, it is 1.33 (ACE) vs. 1.17 (Ulysses).

These differences are intriguing and as yet not understood. A full study, where all elemental ratios observed by Ulysses are compared, awaits the upcoming release of the fully analyzed ACE data set.

3. SUMMARY

We have summarized the solar wind conditions during the Genesis sample collection period, and we have made use of simultaneous composition measurements by the ACE/SWICS instrument to correlate solar wind velocity with elemental abundance. Taking into account new photospheric abundances, we have re-examined the FIP analysis of the Ulysses elemental abundance measurements to find that the FIP enhancement factors for the solar wind are smaller

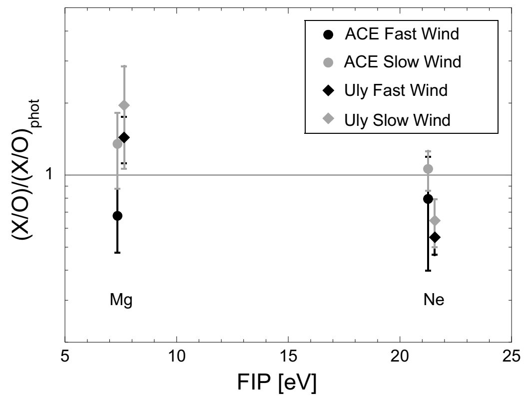

Figure 4. Comparison of ACE and Ulysses Mg/O and Ne/O element abundance ratios. See Fig. 3 for description of plot format.

than previously thought. We have compared the ACE Mg/O and Ne/O abundance ratios to those measured by Ulysses, to find that the ratio of fractionation between Mg and Ne is significantly less for ACE, and that the slow-to-fast wind fractionation is greater for ACE for reasons not understood.

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