LA-UR- 09-06136

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Intended for: Space Research Today

Los Alamos
NATIONAL LABORATORY
EST. 1943

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Roger C. Wiens and the Genesis Science Team

1. Introduction

The compositions of the Earth's crust and mantle, and those of the Moon and Mars, are relatively well known both isotopically and elementally. The same is true of our knowledge of the asteroid belt composition, based on meteorite analyses. Remote measurements of Venus, the Jovian atmosphere, and the outer planet moons, have provided some estimates of their compositions. The Sun constitutes a large majority, > 99%, of all the matter in the solar system. The elemental composition of the photosphere, the visible 'surface' of the Sun, is constrained by absorption lines produced by particles above the surface. Abundances for many elements are reported to the ±10 or 20% accuracy level. However, the abundances of other important elements, such as neon, cannot be determined in this way due to a relative lack of atomic states at low excitation energies. Additionally and most importantly, the isotopic composition of the Sun cannot be determined astronomically except for a few species which form molecules above sunspots, and estimates derived from these sources lack the accuracy desired for comparison with meteoritic and planetary surface samples measured on the Earth.

The solar wind spreads a sample of solar particles throughout the heliosphere, though the sample is very rarified: collecting a nanogram of oxygen, the third most abundant element, in a square centimeter cross section at the Earth's distance from the Sun takes five years. Nevertheless, foil collectors exposed to the solar wind for periods of hours on the surface of the Moon during the Apollo missions were used to determine the helium and neon solar-wind compositions sufficiently to show that the Earth's atmospheric neon was significantly evolved relative to the Sun. Spacecraft instruments developed subsequently have provided many insights into the composition of the solar wind, mostly in terms of elemental composition. These instruments have the advantage of observing a number of parameters simultaneously, including charge state distributions, velocities, and densities, all of which have been instrumental in characterizing the nature of the solar wind. However, these instruments have lacked the ability to make large dynamic range measurements of adjacent isotopes (i.e., $^{17}O/^{16}O$ ~2500) or provide the permil (tenths of percent) accuracy desirable for comparison with geochemical isotopic measurements.

An accurate knowledge of the solar and solar-wind compositions helps to answer important questions across a number of disciplines. It aids in understanding the acceleration mechanisms of the solar wind, gives an improved picture of the charged particle environment near the photosphere, it constrains processes within the Sun over its history, and it provides a database by which to compare differences among planetary systems with the solar system's starting composition, providing key information on planetary evolution. For example, precise knowledge of solar isotopic and elemental compositions of volatile species in the Sun provides a baseline for models of atmospheric evolution over time for Earth, Venus, and Mars.

Additionally, volatile and chemically active elements such as C, H, O, N, and S can tell us about processes active during the evolution of the solar nebula. A classic example of this is the oxygen isotope system. In the 1970s it was determined that the oxygen isotopic ratio in refractory inclusions in primitive meteorites was enriched ~4% in ^{16}O relative to the average terrestrial, lunar, and thermally processed meteorite materials. In addition, all processed solar-system materials appeared to each have a unique oxygen isotopic composition (except the Moon and Earth, which are thought to be formed from the same materials), though differences are in the fraction of a percent range, much smaller than the refractory material ^{16}O enrichment. Several theories were developed over the years to account for the oxygen isotope heterogeneity, each theory predicting a different solar isotopic composition and each invoking a different early solar-system process to produce the heterogeneity. Other volatiles such as C, N, and H may also have experienced similar effects, but with only two isotopes it is often impossible to distinguish with these elements between mass-dependent fractionation and other effects such as mixing or mass-independent fractionation.

Table 1 provides a summary of the major measurement objectives of the Genesis mission. Determining the solar oxygen isotopic composition is at the top of the list. Volatile element and isotope ratios constitute six of the top seven priorities. A number of disciplines stand to gain from information from the Genesis mission, as will be discussed later.

Based on the Apollo solar-wind foil experiment, the Genesis mission was designed to capture solar wind over orders of magnitude longer duration and in a potentially much cleaner environment than the lunar surface (Burnett et al., 2003). A large collection surface area and a wide variety of collection substrates would allow many different investigations with different analysis techniques. The sample return aspect of the mission meant that ground-based instruments are used for measurement. The instruments can be recalibrated and the measurements can be re-made if questions arise. Unlike most space missions, the newest technology can be brought to bear on the problem, even many years after the flight. Writing eight years after the launch of the Genesis mission, these advantages are evident.

2. Payload Design and Sample Analysis Methods

The Genesis payload had several overall goals. The primary goal was to collect solar wind in ultrapure substrates. The highest-purity materials to be found on Earth are typically manufactured for the semiconductor industry. Float-zone (FZ), or zone-refined, silicon grown in an inert atmosphere is one such material, with generally < 10^{15} O/cm^3, approximately three orders of magnitude lower than solar wind implanted over two years, and averaged over the top 100 nm. Czochralski (CZ) silicon, pulled from molten Si in a SiO_2 crucible, is essentially as pure as FZ silicon except for oxygen and carbon. High-fluence neutron-activation studies (M. Ebihara) showed that most elements in either form of Si wafer were at least two orders of magnitude below expected solar wind fluences averaged over the top 100 nm. Silicon was the predominant collector material for the Genesis mission. Slightly over 50% of the total collection area consisted of Si wafers. Other semiconductor materials of similar or slightly lower purity were also used, including detector-grade germanium, sapphire wafers, and a number of thin-film materials such as silicon, aluminum, and gold on sapphire, and diamond-like-carbon on silicon. The variety of substrates proved to be an advantage for the different analysis techniques and also ensured that the mission was not compromised by selecting a single material that ended up having some unsuspected contaminant. Besides the above materials, some additional collection materials were flown for specific purposes. A large Mo on Pt layered foil was flown to search for radioactive particles in the solar wind. The foil used high Z to ensure that spallation products in the mass range of interest were minimized. Also, a bulk metallic glass--a quenched multi-component alloy--was flown specifically for studies using acid etching of the substrates. Finally, a gold foil and a polished aluminum plate were added to utilize available space. These substrates are described in more detail in Jurewicz et al., 2003.

Besides collecting a long-term average sample of solar wind, it was desirable to collect separate samples of the different types of solar wind. There are known elemental composition differences between low-speed (~400 km/s) and high speed (>550 km/s) wind, as well as material identified as from closed magnetic field loops known as coronal mass ejections (CMEs). The high-speed wind emanates from open field line areas known as coronal holes (CH) and appears the most representative of the photospheric composition, while the low speed wind originates in a region known as the streamer belt, a region near the solar equator that tends to have closed field lines. This interstream (IS) wind has a composition more closely representing the corona. The CMEs tend to be high in helium and variable in composition. We wanted to compare long-term averages of the three solar wind types, as well as to obtain a pure sample of the CH wind most representative of the photosphere. To do this required monitoring the solar wind in real time with electrostatic instruments called the Genesis Ion Monitor (GIM) and the Genesis Electron Monitor (GEM) (Barraclough et al., 2003). The instrument data was processed on-board, a first for solar wind data, and a separate collection array was deployed for each type of solar wind.

Another goal was to return a concentrated sample of solar wind to effectively increase the signal-to-background ratio, thereby simplifying the analysis of some elements, especially oxygen. A Concentrator instrument having a 0.4 m diameter aperture was devised which increased the fluence of ions in the 4-30 Dalton range by an average factor of 20 over a 6.4 cm diameter target while suppressing the proton fluence to minimize particle damage (Nordholt et al., 2003). The Concentrator voltages were adjusted constantly, based on real-time solar-wind velocity data from GIM, to optimize the concentration of ions.

Finally, it was desired to have an accurate history of the solar wind conditions during the mission. To this end, the GIM and GEM data, in addition to controlling the regime-collection arrays and concentrator voltages, were downlinked, analyzed, and archived for future studies. These data are available from the Planetary Data System (PDS) and from the Los Alamos National Laboratory website.

Most of the substrates and the concentrator were housed in a payload canister, which facilitated integration as well as providing a barrier against contamination from the rest of the spacecraft. The Canister is shown in open configuration in Fig. 1. The bulk (continuously collecting) solar-wind arrays were located in the lid and at the top of the stack of four arrays. The lower three arrays were for individual regime collection. The substrate areas were maximized by shaping each wafer as a hexagon. For the silicon substrates this required that the normally round wafers be sent out for cutting prior to their final polishing step at the wafer factory (Jurewicz et al., 2003). The canister and array deployments represented potential single-point failures for the mission, as without a complete closure of the canister, the capsule would not survive re-entry through the Earth's atmosphere. Hence, a large torque safety margin was required. The array drive motors had their own housings which vented outside the canister to prevent contamination of the arrays. No non-metallic coatings or paints were allowed in the canister to prevent contamination from outgassing.

A number of analysis techniques were envisioned for use on the returned samples. These included a diverse array of mass spectrometry instruments: noble gas, stable isotope, secondary ion, accelerator, and resonance ionization, as well as synchrotron x-ray fluorescence, total reflection x-ray fluorescence, neutron activation analysis, and gamma-ray analysis of radionuclides. The mission included funding at the several million dollar level to pay for some of the new ground-based instrumentation. One of these was a new hybrid secondary ion mass spectrometer with an accelerator, dubbed the MegaSIMS, built at UCLA (Fig. 2; Mao et al., 2008) particularly to study the oxygen isotopes. At the time of this writing all of the above techniques have been or are being used to obtain new solar-wind results with the exception of neutron and gamma-ray analyses, which are likely too difficult due to either break-up or contamination of samples during the hard landing.

3. Mission Design and Implementation

The Earth is shielded from solar-wind flow by its magnetosphere. To collect solar wind unobstructed by the Earth's magnetosphere a spacecraft is preferably sent upstream of the Earth. The Earth-Sun L1 point, a metastable point 1.5 million km sunward of the Earth provided an ideal region for the Genesis spacecraft. With periodic corrections a spacecraft can be kept in a pseudo-orbit around the L1 point. Other solar-wind-monitoring spacecraft, ACE and WIND, were also using the L1 point. An additional advantage of the L1 point is the ease of returning to Earth. Being a metastable point, only a slight impulse in the direction of Earth brings a spacecraft back to Earth. However, to allow the capsule to re-enter and land during daylight hours, a longer maneuver was necessary, taking the spacecraft back essentially through the L2 point (Fig. 3).

Genesis was launched on August 8, 2001, and began collecting solar wind on November 30. Solar wind was collected continuously until April 1, 2004. The collection went mostly as planned. The solar-wind Concentrator had a lower-than-expected voltage limit on the hydrogen rejection grid, allowing it to reject only about 80% instead of the planned ~90% of the protons. One slight change was made to the regime selection algorithm when it was discovered that the passage of coronal holes can be accompanied by bi-directional electron streaming (Steinberg et al. 2005). Overall the regime-specific CH array collected 32% of the protons, the IS array collected 46%, and the CME array collected 22%, based on the GIM proton measurements. This was a higher than expected fraction for CH, due mostly to a recurring large coronal hole during 2003 (Fig. 4). The CME collection fraction is high due to the use of this array whenever the conditions were in doubt. After 853 days the collector arrays were stowed and the capsule was closed for return.

The re-entry team targeted the Utah Test and Training Range (UTTR), an area characterized by salt flats and a few mountains, but essentially no buildings or humans and little vegetation. The UTTR had the largest restricted air space in the continental US and was equipped with a High-Accuracy Multiple Object Tracking System which could track the capsule as it entered the atmosphere. Returning over land was desired to avoid potential contamination from sea water. Additionally, because of the fragility of the solar-wind collectors, it was desirable to capture the capsule in mid-air. Drop tests from a moving vehicle at UTTR to simulate parachute landing in a strong wind showed that only a few of the collectors were likely to break upon touchdown, but many more could be broken if the capsule were dragged along the ground. Mid-air retrieval of capsules had been done frequently during the cold war, so it was decided to use this technique for the Genesis capsule. The capsule was equipped with a parafoil to provide forward motion during parachute descent, making it easier for an aircraft to approach and capture the payload.

The landing did not go as planned. The capsule came down over the UTTR, but the parachute failed to deploy due to improper installation of the re-entry detection accelerometers. The capsule was in free-fall a full five minutes from the time its image was displayed until it hit the ground. The capsule was dynamically unstable at subsonic speeds, and it impacted on its side (Fig. 5). All but two of the 301 semiconductor wafers used as passive solar-wind collectors were broken by the impact. Fortunately, each collector array had a unique thickness to its collectors, so that each collector shard could be traced back to its proper array. Overall, more than 10,000 collector pieces are now catalogued and are being curated by the team at Johnson Space Center (Allton et al., 2006). Additionally, three of the four concentrator target quadrants were unbroken thanks to the protection afforded by the instrument.

4. Results to Date

Fortunately, many of the analyses can be made on small samples, so that at this point the highest-priority analyses have been successfully completed or are in process. Measurements have been made of solar-wind $^{16}O/^{17}O/^{18}O$, the most important objective (Table 1). These measurements support one of the three long-contended theories for the oxygen isotopic heterogeneity in solar-system objects, indicating that the solar-system underwent a period in which isotopically heavy oxygen was predominantly bonded to water and dust particles in the planet-forming region of the solar nebula due to self-shielding nearer the sun of rays at wavelengths that would preferentially dissociate the $C^{16}O$ molecule. The result is that the earth and other planets are distinctly heavier in oxygen isotopes than the starting material for the solar nebula. These results are awaiting further calibration and instrumental corrections before being published. We are awaiting results from nitrogen and carbon isotopic ratios to see if there might be a similar effect with these elements. Such a result is somewhat expected for nitrogen, but the carbon data from various meteorites suggests that such an effect may not have occurred for that element. If that is the case, it will remain for cosmochemists to further understand the relationships between solids and gases in the early solar system as to why some volatile molecule-forming elements experienced this phenomenon and some did not.

Genesis flew a special experiment for the purpose of observing high-energy noble-gas particles proposed to have been trapped in lunar soils in relatively high amounts. Analysis of this experiment definitively showed that the proposed "solar energetic particles" were simply a part of the normal solar wind which had been more deeply buried and isotopically altered in the implantation process, without the need to invoke a large flux of high-energy particles (Grimberg et al., 2006). This result cleared up a controversy of several decades, which, in an attempt to balance this effect, had resulted in less accurate, or at least less well agreed upon, solar-wind composition values from lunar soils.

Noble gas elemental and isotopic ratios have now been analyzed with relative completeness. Most of the results confirm earlier data from lunar soils but with significantly greater accuracy, approaching ±0.1% for most He, Ne, and Ar isotopic ratios. One outstanding result is that the solar-wind Kr/Xe elemental ratio continues (Heber et al., 2009), as with the lunar soil data, to be significantly lower than photospheric estimates derived from absorption lines of other elements adjacent in the periodic table to Kr and Xe (these noble gases do not have observable solar absorption lines). It remains a strong possibility that the low solar-wind Kr/Xe ratio is due to fractionation during solar-wind acceleration.

The Genesis mission collected separate samples of three different types of solar wind in order to carefully search for isotopic and elemental differences. The results of this study show small but clear differences in the isotope ratios of He, Ne, and Ar between the different regimes. The differences are in the tenths of percent range for isotopes of all elements heavier than helium (Heber et al., 2008). It remains for the space physics community to explain how these differences, as well as the larger elemental abundance differences, arise during acceleration of the solar wind. The modeling of solar wind fractionation will be crucial in accurately estimating solar abundances from solar-wind measurements. To aid in this process we are planning further regime-specific Genesis sample measurements of the isotopes of low-first-ionization-potential elements such as Mg, and of heavy elements such as Xe.

5. Conclusions and Outlook

Let's return to the prioritized list of measurement objectives for the Genesis mission in Table 1. The list spans a number of disciplines affected by these measurements. For example, modeling of the evolution of planetary atmospheres through time will rely on the Genesis measurements for their initial atmospheric compositions. Space plasma physics will be significantly enriched by the understanding of elemental and isotopic fractionation during solar-wind acceleration. And models of the evolution of the solar interior and corona stand to gain from measurements of Li/Be/B and F, respectively, as the former are destroyed in the solar interior, while the latter is produced by spallation reactions at the solar surface.

The discussion in the previous section shows how the highest priorities in Table 1 have been and are being met. We are optimistic that the solar-wind nitrogen and carbon isotopes will be accurately measured in the near future. Measurements listed below these in the table face varying degrees of difficulty. Nuclear anomalies in the elements listed in line 6 could be challenging due to the very small nature of these anomalies in meteoritic materials. Team members are now analyzing Mg isotopes as a first test of this objective. For the elements in line 10 (Li, Be, B), the high survival rate of concentrator target materials suggests it could be used, especially since diamond-like carbon, one of the Concentrator collector materials, has a very low diffusion rate for these elements. Identification of the elemental abundances and a factor-of-two measurement of the isotope ratios is all that is needed.

Finally, several of the original objectives may not be met. Table 1 lists Objectives 7 and 13 as potentially not viable. The measurement of radioactive isotopes in the solar wind (#13) was to be done with special substrates which ended up being contaminated during manufacturing, but was not detected until after launch. The contamination issue was greatly exacerbated by the hard landing. Objective 7 was to measure the abundances of solid elements surrounding Kr and Xe in the periodic table. By comparison with these noble gases, we hoped to understand whether the sun was enriched or depleted in gases relative to solids. The gas-solid comparison is best done with relatively heavy elements where nuclear theory gives specific predictions of relative abundances (Wiens et al., 1991, 1992). However, the options for analyzing these elements are more limited because of the crash.

In conclusion, in spite of being written off by the media at the time of the crash, the Genesis mission is already a significant success. As with the lunar samples returned from the Apollo missions, we expect the Genesis samples to continue yielding the secrets of the Sun for many years to come. A great advantage of sample-return missions (along with surviving crash landings) is that advances in instrumentation can continually improve the measurements many years after the mission. Thus it may be possible that several decades from now many new findings from this mission will greatly exceed our expectations today.

Figures

Fig. 1. Genesis science canister during assembly at Johnson Space Center. The lid (front right) contained one array of solar-wind collection wafers, while the body (left) contained the solar-wind concentrator (gold), a stack of four collector arrays, and their deployment motors. (NASA photo.)

Fig. 2. An example of the type of instrument that cannot be miniaturized and flown. Shown here is the UCLA MegaSIMS, which is a combination of secondary ion mass spectrometer and an accelerator mass spectrometer (Mao et al., 2008). The sample is introduced at the far left of this fish-eye view of the instrument. The beam line extends the length and width of the room, with the detectors contained in the large tank at right. (NASA photo.)

Fig. 3. Genesis trajectory projected into the ecliptic, shown to scale with the lunar orbit, with the Earth and Sun (off to left) as fixed reference points.

Fig. 4. Percentage distribution of solar-wind regimes on a monthly basis from 2001 to 2004 during the Genesis mission. The beginning and end of the sample collection period are indicated by vertical dashed lines.

Fig. 5. Genesis capsule shortly after a hard landing in the Utah desert. The parachute deck is on the right and the heat shield (mostly hidden) is on the left. The science canister (Fig. 1) is sandwiched between the upper deck (center) and the heat shield. (NASA photo.)

Fig. 1

Fig. 2.

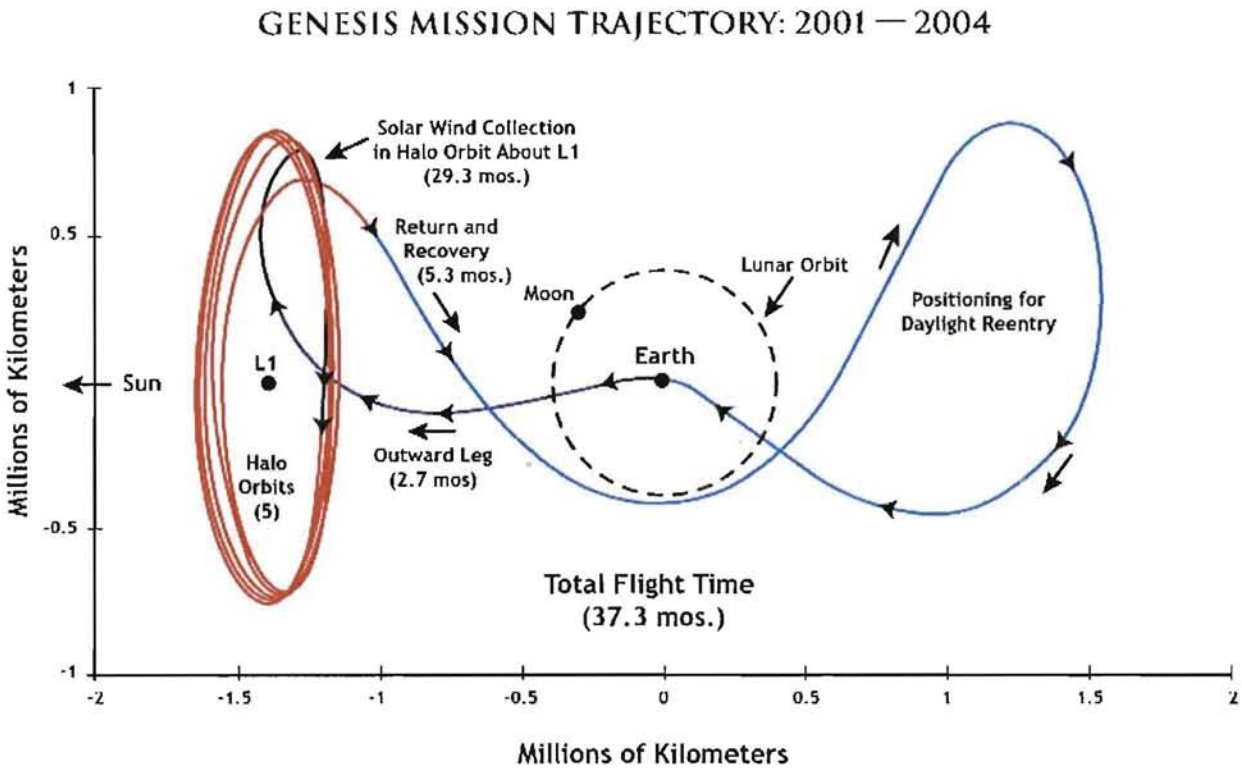
GENESIS MISSION TRAJECTORY: 2001 — 2004
Solar Wind Collection in Halo Orbit About L1 (29.3 mos.)
Return and Recovery (5.3 mos.)
Moon
Lunar Orbit
Positioning for Daylight Reentry
Earth
L1
Sun
Halo Orbits (5)
Outward Leg (2.7 mos)
Total Flight Time (37.3 mos.)
Millions of Kilometers
Millions of Kilometers
1
0.5
-0.5
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

Fig. 3

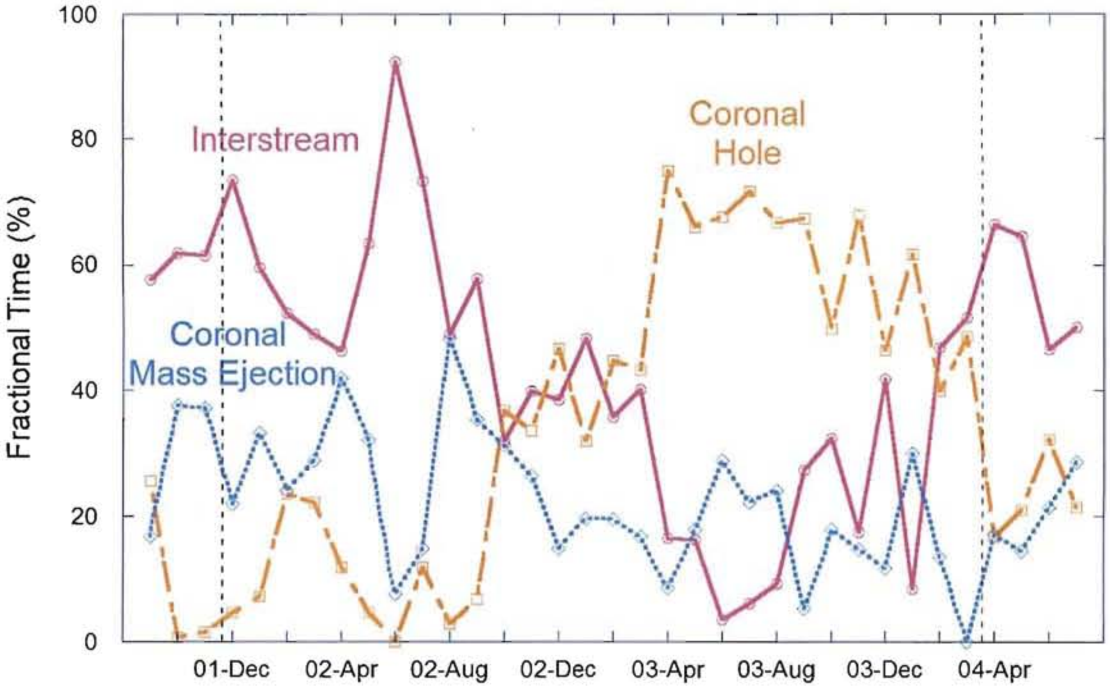
100
80
60
40
20
0
Fractional Time (%)
Interstream
Coronal
Hole
Coronal
Mass Ejection
01-Dec
02-Apr
02-Aug
02-Dec
03-Apr
03-Aug
03-Dec
04-Apr

Fig. 4

Fig. 5

Table 1

GENESIS mission measurement objectives

Measurement Objective		Field	Success?
1	$^{18}O/^{17}O/^{16}O$	O	Y
2	$^{15}N/^{14}N$	O, A	M
3	Noble gas elements & isotopes	A, O	Y
4	Isotope differences in solar-wind regimes	P	Y
5	$^{13}C/^{12}C$	O, A	M
6	Nuclear anomalies: Mg, Ca, Ti, Cr, Ba	O	M
7	Solid-gas element ratios in the Sun	O, S	N?
8	Solar-terrestrial isotopic differences	O	M
9	High-energy solar particles	P, S	Y
10	Li, Be, B	S	M
11	F	S	M
12	Heavy-light element abundances	S, P	M
13	Radioactive nuclei	S	N?

O = Origins & Cosmochemistry, A = Planetary Atmospheres, P = Space Plasma Physics, S = Solar Physics
Y = yes, M = maybe (not yet done), N = no

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