The Genesis Discovery Mission: Return of Solar Matter to Earth

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Abstract

The Genesis Discovery mission will return samples of solar matter for analysis of isotopic and elemental compositions in terrestrial laboratories. This is accomplished by exposing ultra-pure materials to the solar wind at the L1 Lagrangian point and returning the materials to Earth. Solar wind collection will continue until April 2004 with Earth return in Sept. 2004. The general science objectives of Genesis are to 1) to obtain solar isotopic abundances to the level of precision required for the interpretation of planetary science data, 2) to significantly improve knowledge of solar elemental abundances, 3) to measure the composition of the different solar wind regimes, and 4) to provide a reservoir of solar matter to serve the needs of planetary science in the 21st century. The Genesis flight system is a sun-pointed spinner, consisting of a spacecraft deck and a sample return capsule (SRC). The SRC houses a canister which contains the collector materials. The lid of the SRC and a cover to the canister were opened to begin solar wind collection on Nov. 30, 2001. To obtain samples of O and N ions of higher fluence relative to background levels in the target materials, an electrostatic mirror ("concentrator") is used which focuses the incoming ions over a diameter of about 20 cm onto a 6 cm diameter set of target materials. Solar wind electron and ion monitors (electrostatic analyzers) determine the solar wind regime present at the spacecraft and control the deployment of separate arrays of collector materials to provide the independent regime samples.

Introduction

Genesis is the fifth in NASA's low-cost line of missions called Discovery. The overall purpose of the mission is to collect samples of solar wind and return them to earth. Following launch on Aug. 8 2001, the Genesis mission began collecting samples of solar matter on Nov. 30, 2001. Exposure of collector materials will be for 27 months near the L1 Sun-Earth libration point. The overall mission trajectory is shown in Figure 1. These samples will return to Earth for laboratory isotopic and chemical analyses on Earth on Sept 8, 2004. At that time the real Genesis science mission will begin. This paper summarizes the pre-return science rationale and mission technical approach to provide context to the following important and substantial instrument papers.

Science Background

The science goals of NASA are to understand the formation, evolution, and present state of the solar system, the galaxy, and the universe. Most planetary missions investigate the present state of planetary objects. By, in effect, going back in time, Genesis addresses questions about the materials and processes involved in the origin of the solar system by providing precise knowledge of solar isotopic and elemental compositions.

The context for the interpretation of Genesis data is a wide spread consensus on a "standard model" for the origins of planetary materials. This model assumes that (1) planetary materials and objects arose from a compositionally homogeneous solar nebula. (2) With the exception of D and the Li isotopes, the elemental composition of the nebula is preserved in the solar photosphere and (3) With the exception of part per thousand or less mass dependent isotopic fractionations due to physico-chemical processes, isotopic compositions are the same in all parts of the solar system and thus equal to terrestrial values. Genesis data can be used to refine the standard model, but more importantly, test its assumptions.

For Genesis, the solar wind is just a convenient source of solar matter readily available outside the terrestrial magnetosphere. Solar wind ions have velocities in the well-understood ion implantation regime and are essentially quantitatively retained upon striking passive collectors. (Small backscattering loss corrections can be accurately made.)

Solar wind collection was demonstrated by the highly successful Apollo solar wind foil experiments (Geiss *et al*., 1972). The Apollo foils were only sufficiently pure for the study of He, Ne, and ^{36}Ar. With 100-times longer exposure and, especially, with purer collector materials, the goal of Genesis is to provide precise solar isotopic compositions and greatly improved solar elemental composition for most of the Periodic Table.

General Science Objectives

Analysis of the collector materials will give precise data on the chemical and isotopic composition of the solar wind. By returning samples of solar matter to Earth, the Genesis mission will provide:

(1) Isotopic abundances of sufficient precision to address planetary science problems.
(2) Major improvement in our knowledge of the average chemical composition of the solar system.
(3) Independent compositional data on 3 different kinds of solar wind (we refer to these as "regimes".)
(4) A reservoir of solar material to be used in conjunction with advanced analytical techniques available to 21st century scientists.

Items (1)-(3) will be discussed further below. The Sample Allocation and Curation section summarizes how we meet Objective (4).

Solar Isotopic Compositions The standard model predicts the same isotopic compositions for all solar system materials; however, measurable heterogeneities exist in the isotopic compositions of some, but not all, elements among various planetary materials. Thus, solar isotopic compositions should be the reference point for comparisons with planetary matter. The specific cases of O and N will be discussed below.

Any measurable isotopic difference is of great importance because, in many cases, these cannot be explained by the same chemical and physical processes which are usually invoked to explain elemental differences (e.g. differences in temperature). It is independently known that the solar system was formed from a wide variety of stellar materials produced over the 5-10 billion years of galactic history prior to the formation of the solar system and that these materials had a great diversity of isotopic compositions. The isotopic compositions of solar matter thus define the average of these diverse inputs and thus represent an anchor point for the interpretations of the isotopic differences among planetary materials. Isotopic variations are expected given that the observed isotopic compositions are the result of mixing and that the mixing may not have been complete. However, there is no *a-priori* constraint on the magnitude of variations. For many elements, the variations among presently-available extraterrestrial materials are less than parts in 10^3 to 10^4, indicating rather thorough mixing.

Solar composition is important for astrophysics and solar physics, but planetary science requires greater elemental coverage and much higher levels of precision, especially for isotopes. For example, most theories of stellar nucleosynthesis are considered successful if solar system isotope ratios are reproduced within a factor of 2. By contrast, isotopic measurements of terrestrial, lunar, Martian, and meteoritic materials typically deal with 0.1% and smaller differences. In atmospheric modeling, differences of 1 percent or less are crucial for, e.g., $^{38}Ar/^{36}Ar$ and the Xe isotopes. As discussed below, O and N are important exceptions, showing a range of around 5% (for both $^{18}O/^{16}O$ and $^{17}O/^{16}O$) and 60% for $^{15}N/^{14}N$. For comparison the most precise spacecraft measurement of $^{18}O/^{16}O$ has uncertainties of ±20% and ^{17}O cannot be detected with present instruments. (Wimmer-Schweingruber et al., 2001).

Elemental Abundances. The observed diversity in solar system objects is chemical in origin. Quantitatively, diversity can be defined as the difference in planetary material composition from solar composition, illustrating the importance of solar elemental abundances. The present best source of solar abundances comes from analysis of photospheric absorption lines in the solar spectrum. A small number of elements have quoted errors of ±10% (one sigma), but overall there are large uncertainties in these abundances and a significant number of elements cannot be measured. Thus, compilations of "solar" abundances for non-volatile elements are currently based on analyses of carbonaceous (CI) chondrite meteorites. The limitations to this have been discussed (Burnett et al., 1989; McSween, 1993). Solar abundances should be based on solar data. For example, it is likely that new CI-like meteorites will eventually become available which will have slightly different abundances than known CI meteorites, presenting a major challenge to how well we think we know solar abundances. If solar composition is based on solar data, we are immune to such periodic perturbations. The best hope for major improvement in knowledge of solar abundances is the solar wind. The Genesis goal is to improve knowledge of solar elemental abundances by at least a factor of 3 for each element.

Solar Wind Regimes It is well established that the solar wind is accelerated by more than one mechanism, leading to three major solar wind regimes: high-speed streams from coronal holes, low-speed interstream wind, and the transient wind associated with coronal mass ejections (Neugebauer, 1991; Fisk et al., 1998). Measurements by in-situ solar wind instruments have shown that there is an *elemental* fractionation of matter between the photosphere and the solar wind, which depends on the first ionization time (FIT) and, perhaps to a much lesser extent, on the ion mass and charge (e.g. Marsch et al., 1995; von Steiger et al, 2000). Genesis will collect separate samples for each of these three regimes in order to provide better elemental data on compositional differences among the three regimes (Neugebauer, et al. 2002).

The data for the individual regimes provide a critical test of the accuracy of the corrections of *elemental* abundance data for FIT fractionation effects. We will combine the Genesis solar wind monitor data (Barraclough et al., 2002) with knowledge of the high time resolution systematics of FIT, mass, and charge fractionation patterns obtained from the results of the Ulysses, WIND, SOHO, and ACE missions to model the corrections to be applied to the Genesis sample data to deduce the photospheric elemental composition. It should be emphasized that the observed FIT variations appear only to affect elements with relatively high ionization potential. Present data are consistent with no fractionation relative to photospheric abundances for elements with a first ionization potential less than about 9 eV, which includes most of the Periodic Table and especially all the rock-forming elements which make up the terrestrial planets. For these elements, corrections, if any, appear to be small, but this will be directly assessed by Genesis data. It will not be necessary to *assume* that the corrections are small. Genesis will provide three independent regime data sets which will have different amounts of correction, but yet must give the same corrected photospheric composition. This should provide proof that our derived photospheric elemental abundances are correct.

Although the FIT fractionations are based on elemental properties and thus should not produce isotopic variations, isotopic variations are still possible (e.g. Bochsler, 2000). There is some evidence for transient isotopic variations under different solar wind conditions (Kallenbach et al., 1999; Kallenbach, 2001). Except for $^{3}He/^{4}He$ which shows large transient variations, reported variations are at the precision limits of spacecraft instruments, typically 10-20%, 2 sigma. With the Genesis samples, systematic searches for long term isotopic variations between solar wind regimes can be carried out with much higher precision, 1% (2 sigma) or better for many elements. If variations are found, these will be very important data for solar physics but a complication for the Genesis goals, as corrections will be required to obtain photospheric isotopic compositions. Of course, the solar physics theories developed to account for any regime variations are the basis for correction back to photospheric compositions, illustrating the strong complementarity between Genesis and solar physics goals.

Examples of Specific Measurements

Mission science planning, especially the selection and testing of collector materials, was based on a set of prioritized measurement objectives. Our three highest priority objectives are discussed here. The others, along with other Genesis science documents, are discussed at http://www.gps.caltech.edu/genesis/

The highest priority specific objectives are to measure the relative amounts of:

- O isotopes, because they provide the basis for understanding observed meteorite variations (e.g. Clayton, 1993; Wiens et al., 1999).
- N isotopes, because they are a key reference point in the eventual understanding of large but totally unexplained, N isotopic variations in planetary materials (e.g. Owen et al., 2001).
- Noble gas isotopes and elements, because they provide the basis for interpreting the compositions of terrestrial planet atmospheres (e.g. Pepin, 1991).

O Isotopes Figure 2 is a schematic summary of O isotopic variations in planetary materials, recognizing that all data come from materials residing at 1-3 AU. The scales have a total range of about 8%, and on this scale, as indicated on Figure 2, the error bars on spacecraft or spectroscopic solar data are larger than the figure. Most meteoritic (asteroidal) materials have O isotopic compoistions which lie within a few % of the Earth, Moon, and Mars; however CAI materials (Ca-Al-rich inclusions) from chondritic meteorites show large ^{16}O enrichments. Different models for the origin of the variations predict the location of the solar isotopic composition. One of these (Clayton and Mayeda, 1984) is indicated by the point SM. Other models (e.g.

Clayton, 2002) predict that the solar O isotopic composition lies at the most ^{16}O-rich end of the CAI trend. The Genesis precision indicated on Figure 2 can clearly distinguish between these and other models. On a more model-independent basis, a precise measurement of the solar O isotopic composition addresses the fundamental issue of the degree of gas-dust mixing that occurred in the solar nebula for the solid materials that now comprise the inner solar system (Wiens et al., 1999). As they are rocky materials, inner solar system bodies can, in principle, be made from the dust phase of the solar nebula. If isotopic equilibrium between gas and dust was not established prior to dust-gas separation, significant differences could exist between the solar O isotopic composition and any inner solar system material. Operationally, if the solar O isotopic composition measured by Genesis lies close to the Earth-Moon-Mars-asteroid region of Figure 2, it would be indicative of a high degree of gas-dust equilibration. However, if gas-dust equilibration did not occur, the solar O isotopic composition could be significantly displaced from the Earth-Moon-Mars-asteroid region of Figure 2, and this would be our interpretation of a significant displacement.

N and noble gases These elements are closely coupled.. In Figure 3, the $^{15}N/^{14}N$ ratios are expressed as a % difference from the present day terrestrial atmosphere, although this is clearly an arbitrary reference. The Apollo solar wind foils provide a precise value for solar wind $^{20}Ne/^{22}Ne$, with the solar wind Ne isotopic ratio being 38% higher than the value for the terrestrial atmosphere. The difference is of major importance, very likely indicating that the Earth has experienced major atmospheric loss (e.g. Pepin, 1991). If this is true, then differences are also expected between the solar and terrestrial isotopic compositions of N and the other noble gases. Thus, Genesis will provide major quantitative tests of the atmospheric escape models. Figure 3 is a top level summary indicating that exceptionally large variations in $^{15}N/^{14}N$ characterize different solar system reservoirs For purposes of illustration, a crude estimate of the pre-escape terrestrial atmospheric $^{15}N/^{14}N$, scaled from the $^{22}Ne/^{20}Ne$ differences, is shown as "Ancient Earth" on Figure 3. The exact displacement is highly uncertain; nevertheless, the pre-escape atmospheric $^{15}N/^{14}N$ should be distinctly less than the present day $^{15}N/^{14}N$.

The N and noble gases measured in lunar regolith samples are expected to be of solar origin (e.g. Kerridge, 1989); however, impact heating alteration of lunar surface materials has made the extraction of quantitative solar wind abundances difficult. Over the last 3 decades, an approximate consensus has emerged on "solar" noble gas elemental and isotopic ratios from lunar regolith samples (e.g. Ozima et al., 1998); however, there are many assumptions in arriving at the consensus composition. At the minimum, Genesis data will provide ground truth for the validity of these assumptions. Further, there is strong evidence for time variations in the solar noble gas elemental ratios (Wieler et al., 1996), although not in the isotopic ratios (Ozima et al). Another goal of Genesis is thus to provide present-day solar noble gas elemental and isotopic abundances to help realize the unfulfilled Apollo goal of "understanding the Sun in time" from the study of lunar samples.

In contrast to the noble gases, there is no consensus on the interpretation of the important and fascinating data for N in lunar regolith samples (e.g Kerridge, 1989). The lack of understanding of N introduces significant uncertainties in the derived solar noble gas abundances. The N/noble gas ratios are a factor of 10 higher than would be expected from present photospheric abundance estimates. Moreover, N isotopic compositions show a lot of variability with a tendency for samples exposed on the lunar surface in the past to have lower $^{15}N/^{14}N$ than present-day surface soil samples (Figure 3). The ancient-recent trend indicated for the lunar data in Figure 3 is a highly oversimplified, but "traditional" interpretation in which there has been a "secular" increase of the solar wind N isotopic composition with time. The prediction for Genesis from the traditional view is that the present-day solar wind $^{15}N/^{14}N$ should be significantly higher than that for the terrestrial atmosphere.

A direct measurement of solar wind $^{15}N/^{14}N$ from SOHO (Kallenbach, et al., 1998b) gives a higher value than the terrestrial atmosphere, but not outside a 2 sigma error limit (Figure 3). This is in apparent support of a secular increase in solar wind $^{15}N/^{14}N$; however, there is no known solar physics mechanism to cause such secular variations. Moreover, there are some lunar samples which do not fit the simple ancient-recent trend, and more complex time dependences have been proposed (e.g. Kerridge, 1989). These problems have led to many suggestions that the bulk of the N in the lunar regolith samples is not solar in origin (e.g. Hashizume et al., 2000).

As indicated on Figure 3, the Galileo probe measured $^{15}N/^{14}N$ significantly less for the Jovian atmosphere than the terrestrial atmosphere (e.g. Owen et al., 2001). Given the large uncertainties, the ancient Earth, ancient lunar, and Jupiter data would be consistent with a homogeneous solar system $^{15}N/^{14}N$ roughly 30% lower than the terrestrial atmosphere, but this hypothesis is totally contradicted by the SOHO data. Because of interferences from doubly-charged Si ions, the $^{15}N/^{14}N$ is a difficult measurement for the SOHO instrument. If Genesis data confirm the SOHO, it would suggest a previously-unrecognized major heterogeneity between the materials of the inner and outer solar system.

A large range in $^{15}N/^{14}N$ is observed in meteoritic materials (e.g. Kerridge, 1995). The extreme meteoritic values would go to +150 on the scale of Figure 3. The origins of these variations are totally unknown. Surviving presolar materials produce large variations in meteoritic noble gas isotopic ratios, but the numbers of atoms from pre-solar materials is rather small. Much larger amounts of presolar N would be required, making the observed variations difficult to understand as pre-solar grain effects. The observed meteoritic $^{15}N/^{14}N$ ratios tend to be higher than the terrestrial atmosphere; this suggests (but certainly does not prove) that meteoritic or cometary inputs might be the source of the high $^{15}N/^{14}N$ measured in recent lunar regolith samples.

In any case the large range of $^{15}N/^{14}N$ shown on Figure 3 represents a serious challenge to the standard model of a homogeneous solar nebula which predicts uniform initial isotopic compositions for solar system objects. An understanding the origins of the isotopic variations shown on Figures 2 and 3 would unquestionably produce greater insight into how planetary materials and objects formed.

Analysis Requirements

The levels of analytical sensitivity needed for the various elements and their isotopes depend upon their fluences in the solar wind, on the contamination background expected in the collector materials, and on their relative importance to planetary science. Table 1 gives our predictions for the fluences of different elements. Analysis of Genesis samples requires sensitivities of parts per million to parts per trillion (depending on the element) in the outer 100 nm of the collector materials surfaces.

The preceding discussion shows the need for data with high precision/accuracy. Table 2 provides our estimates of the required levels of accuracy and precision required for fundamental advances in understanding planetary materials. Genesis collector materials (see Jurewicz, et al, 2002) have been selected and analytical techniques identified which will support reaching the goals set out in Table 2.

Instrumentation Overview

Figure 4 is a block diagram showing the interdependence of the GENESIS instrumentation and its unique strategy.

In common with all sample return missions, the science objectives are not achieved until the returned samples have been analyzed. This means that not all of the mission instruments are launched. Sample collection instruments are launched (Collector Arrays and Concentrator in our case), but the sample analysis instruments are not. Analytical instruments to be used on the returned samples will certainly include, but not be limited to, noble gas mass spectrometry, static stable isotope mass spectrometry, secondary ion mass spectrometry, resonance ionization mass spectrometry, accelerator mass spectrometry, inductively coupled plasma mass spectrometry, thermal ionization mass spectrometry, and neutron activation analysis.

The spacecraft instruments consist of the following

The **Collector Arrays** (passive collectors in Figure 4) are arrays of ultrahigh-purity materials, assembled under clean-room conditions (background for Figure 5), and placed in a clean science **Canister** which is integrated as a unit into the return capsule. Some arrays are always exposed to collect a "bulk" solar wind sample, while others are deployed only in specific solar wind regimes. Each collector array is made up of 54 full hexagons (approximately 10 cm point to point) and 6 half-hexagons of individual collector materials. More information on the collector array materials is found in the accompanying paper by Jurewicz et al., 2002.

The **Concentrator** is an electrostatic reflecting telescope which mirrors solar-wind ions and concentrates the fluence by a factor of 20 on a set of target materials at the focal point. Ions in the mass/charge range 2.0 to 3.6 amu/q (He through Mg in terms of elements) are concentrated to obtain high signal-to-background ratios, especially for measurement of N and O isotopes. Such concentration is necessary for measuring these isotopic ratios, which are the highest priority science objectives. The Concentrator is described in detail in the accompanying papers by Nordholt et al. 2002, and Wiens et al., 2002.

Recognition of different solar wind regimes is accomplished with standard solar wind ion and electron **Monitors (**Barraclough et al. 2002). The output signals of the monitors are analyzed by a "science algorithm" (Neugebauer et al. 2002) to determine the prevailing solar wind regime and to deploy autonomously the appropriate Collector Array. The output of the monitors is also used to set voltage levels in the Concentrator and to determine the total fluence of H and He to the arrays.

The Collector Arrays are contained in the **Canister** (Figures 4 and 5). As shown on Figure 6, there are a total of 5 arrays, one of which is fixed in the Canister Cover and the other four deployable arrays vertically stacked. The 4 deployable arrays are rotated clockwise 256 degrees to expose the Concentrator to the solar wind. The fixed array and the top array of the stack are always exposed and thus collect a bulk solar wind sample. Depending on the prevailing solar wind regime, as determined by the monitors, one of the three bottom arrays in the stack is unshaded by an 152 degree counterclockwise rotation on the shaft of the Array Deployment Mechanism relative to the configuration shown in Figures 4 or 5. When the monitors record a change in the solar wind regime, the previously unshaded array is shielded from the solar wind by being placed back in the stack and the appropriate new array unshaded.

At the completion of solar wind collection in April 2004, the stack of deployable arrays will be stowed by rotation back inside the canister. The Cover Drive Mechanism will be activated to close the Canister Cover. The Lock Ring Drive Mechanism is rotated to seal the Cover to the Canister Base and to latch it for the return back to Earth. Inside the canister, each Array is firmly held between the Fixed Saddle (Figure 5) and the Deployable Saddle (Figure 6), which is rotated inward against the Array Stack by the action of the Lock Ring Drive to clamp the Arrays.

To prevent contamination on Earth return, a Filter (not shown) is installed in the Canister Base. This has been tested to demonstrate removal of particulates greater than 0.3 microns in size and to effectively getter gases. The Canister was placed on a high purity nitrogen gas purge from the end of integration until a few hours before launch. This purge will be re-established as soon as possible after recovery.

The strict cleanliness requirements levied on the Canister and its contents demanded changes from the normal development and test flow for spacecraft hardware. The flight model Canister was built and tested using non-flight collectors identical to those being flown. After complete testing, including vibration and solar-thermal vacuum testing, the Canister was completely disassembled. The structure and array frames were cleaned in a class-10 cleanroom, re-assembled, and the array frames were populated with fresh, clean collectors. After installation of the concentrator, the Canister was closed in the class-10 cleanroom and was never opened again until in space.

Spacecraft

The Genesis spacecraft was designed to be a sun-pointing major axis spinner, consisting of an equipment deck and a sample return capsule (SRC). The equipment deck provides–structural support for the spacecraft subsystems, the Ion and Electron monitors and the SRC. The SRC contains the science canister and its payload described above.

Figure 8 shows the overall spacecraft with the SRC attached to the upper side of the deck. The two solar arrays are capable of generating 281 watts at 1.012 A.U., 10° off-sun, 65°C at end of life. A rechargeable 16 amp-hr, 28 V spacecraft battery provides power during maneuvers if the spacecraft is pointed away from the sun. Redundant low gain antennas are mounted to the solar arrays on both front and aft sides. Redundant transponders are used to support communications with the Deep Space Network (DSN) stations. The two propellant tanks visible at the edge of the deck each hold more than 71 kg of useable hydrazine. Figure 8 also highlights the lower deck, or underside, of the spacecraft. The spacecraft battery is located inside the launch vehicle adapter ring. The medium gain antenna provides high data rate communications with the DSN during science data transmission. The spacecraft employs passive thermal control plus autonomous and ground-controlled heaters.

The lower portion of Figure 8 also shows various elements of the attitude control subsystem (ACS). To avoid contamination on the collector arrays, all thrusters are below the spacecraft deck, out of any line of sight of the SRC. Eight small (0.9 N) reaction control system thrusters, canted from the spin axis, are used to control the spin rate, precess the spin axis daily, and perform small delta-V maneuvers. Large delta V maneuvers are performed with four large (22 N) trajectory correction maneuver thrusters, axially directed.

There are three attitude sensor types: digital 2-axis sun sensor (DSS), spinning sun sensor (SSS) and star tracker (ST). The spinning sun sensor measures the sun crossing angle. The digital sun sensor is a two-axis version of the SSS, but mounted with a view along the spin axis. SSS and DSS processed output provides spin axis off-sun angle and spin rate. Under high nutation and/or sun proximity to the spin axis, multiple sun crossings can occur at irregular time intervals. These can severely degrade knowledge of the spin rate. Sun pointing keep out zones were established to avoid this occurrence. Mission flight rules, and both flight and ground software, enforce the keep out zones.

ACS is also responsible for the passive nutation damper system. This system consists of a viscous fluid filled tube that surrounds each propulsion tank and fluid control system. The shorter the nutation time constant, the quicker nutation is damped out. In general, the time constants diminish as fuel is expended and/or spin rate is increased. A typical time constant is 2.5 hours when the spacecraft has half its fuel left, in the science configuration, at the nominal 1.6 rpm spin rate.

A unique challenge for Genesis was to design the spacecraft so its principal axis remained aligned with the spin axis in several different configurations, minimizing wobble. The initial and final configurations are with the SRC closed. Alignment in this configuration is driven by the need for accurate pointing when the SRC is released for re-entry. The post-launch check-out configuration had the SRC lid open but the science canister closed prior to L1 orbit insertion. And finally, in the science collection phase the canister lid is open and the arrays are deployed. The position of the arrays also affect spacecraft wobble. Adjustment of the SRC lid angle aids in minimizing wobble among the various configurations in which the lid is open. The SRC lid angle is currently 192.2° in the science-collection phase, and was 192.9° during portions of the check-out phase. Analysis of the first several months of operation shows that the wobble remains under 0.35° in the science-collection orientation, and under 0.2° in all other orientations. This is sufficient to meet the (wobble+nutation) requirement, which is driven by the ion temperature measurement.

The Command and Data Handling (C&DH) subsystem is housed on the spacecraft's forward deck. The C&DH provides time definition and command and data interfaces with all other subsystems. It is fully redundant and single fault tolerant. In operation, it has proved quite resistant to solar proton events. The C&DH contains multiple processor and memory cards and virtual memory buses. Some of the principal cards are the Flight Processors that contain the central processor unit, dynamic random access memory (DRAM), two different backup memory devices, the Payload and Pointing Interface Card (PPIC), and the Command Module Interface Card (CMIC). Flight Software (FSW) includes the onboard code which runs the spacecraft, including fault protection. FSW has a selectable operating speed and utilizes less than 60% of processor capability. 128 MB (megabytes, 1024x1024x8 bits) of DRAM is used for all operations. FSW has been allocated 32 MB, and telemetry storage has been allocated 96 MB for science and engineering data. This is sufficient for multiple playbacks in the current downlink strategy.

Fault protection is responsible for failure detection, response and recovery. A hierarchical detection strategy isolates the failure. Responses include switching from primary to redundant strings and/or swapping C&DH sides. If needed, an autonomous safe mode is entered which reconfigures the vehicle to minimize electrical power loads, continues fault detection and response, and (if the spacecraft is > 35° off sun) precesses quickly to a sun pointed attitude for solar array power.

The original mission plan called for spacecraft contact with the DSN only once per week during the science phase of the mission. A more conservative strategy was eventually implemented in which contact is established approximately three times per week during routine portions of the mission and more often during high-activity phases. This allows multiple playback opportunities for the data and more frequent monitoring of the spacecraft's state of health. Upon transmission to Earth, the data are received by either 26-m or 34-m DSN antennas. There are 8 downlink data rates, from 1050 to 47400 bits per second, depending on spacecraft antenna, DSN antenna, and mission phase.

The sample return capsule (SRC) contains all of the payload to be returned to Earth, as well as re-entry support systems. It is a clamshell design, built to allow exposure of the collector materials in space and protect them during re-entry. The upper half of the clamshell contains the descent parachute. The lower half, enclosed by the heat shield, contains the payload canister surrounded by the avionics components required for recovery of the capsule. These include a patch antenna, VHF locator beacon, GPS receiver, UHF transceiver, SRC battery, and supporting electronics. The GPS receiver is used to give the position of the incoming capsule once the parachute is deployed to support mid-air capture by helicopter. The locator beacon is included as a backup, in the event of a contingency ground recovery. The beacon signal is intended to last a number of hours after landing. Details on capsule recovery are given below.

More details on spacecraft subsystems are given in Hong et al. (2002; C 2002 IEEE).

Mission Operations and Recovery

The GENESIS mission trajectory is shown in Figure 1. Following launch on August 8, 2001, the GENESIS spacecraft underwent a check-out period during approach to the L1 position. The monitors were turned on August 23, 2001 and in-situ testing of the science algorithm commenced. A check-out phase of approximately three months prior to opening the Canister allowed several solar rotations over which to test the identification of the different solar-wind regimes (Neugebauer et al., 2002). This time was also used to outgas the spacecraft in order to minimize any possible contamination to the collector arrays. The return capsule lid was open either partially or fully during this time to facilitate outgassing.

The spacecraft underwent L1 orbit insertion on November 19, 2001, and the Canister was opened shortly thereafter, on November 30, to begin solar-wind collection. During the collection phase, the spacecraft maintains an orientation with the spin axis pointed 4.5±2.0 degrees ahead of the sun, which is the average apparent direction of the solar wind, considering spacecraft motion around the Sun. The spacecraft autonomously performs a one-degree precession maneuver each day to maintain this position as it orbits the Sun along with the Earth. The spacecraft also maintains a spin rate of 1.6 rpm ±10%, which allows the monitors to sweep over 360° in the azimuth angle about the spin axis at regular intervals. The collection phase is slated to continue until April, 2004 with only minor interruptions for station-keeping maneuvers. These maneuvers occur approximately six times per year, expending only 1-2 days each of potential collection time. Thrusters used for these maneuvers and also for daily precession maneuvers are all biased away from the front of the spacecraft--and from the collector arrays--to minimize potential contamination to the arrays during thruster firings.

At the end of the collection period in April, 2004, the Canister and SRC are closed, and a small maneuver begins the journey back to Earth. Figure 1 shows that instead of returning directly to Earth, the spacecraft takes a more circuitous route through the L2 region before re-entry in order to allow re-entry to occur at relatively high latitude at the Utah Test and Training Range and on the daylit side of the Earth. In case of bad weather in Utah, (which would be unusual for this time of year) diversion to a "parking orbit" is possible which can delay the spacecraft's reentry for up to 19 days.

Before reentry, the spacecraft will assume a nose-down reentry attitude. The capsule stabilizes with its nose down because of the location of its center of gravity, its spin rate and aerodynamic shape. The spacecraft spins up to about 16 revolutions per minute, then the SRC separates. The remainder of the spacecraft will execute a deboost maneuver so that it reenters Earth's atmosphere and burns up over the Pacific Ocean. The SRC will enter Earth's atmosphere at an entry angle of minus 8 degrees at Earth escape velocity (11.04 kilometers per second).

At 30 kilometers altitude, the capsule will deploy a drogue parachute to begin slowing its descent. That in turn will pull out the main parachute, a parafoil which descends in a broad spiral producing a low vertical descent velocity. The parafoil size determines its airspeed, which is chosen for best mid-air retrieval safety and reliability.

Mid-air retrieval is accomplished by helicopter snatch. Two helicopters (primary and backup) will provide up to 5 passes. Radar and infra-red tracking will guide the helicopters to the SRC. The mid-air retrieval subsystem consists of a constant tension winch, a single pole that pivots off the pilot-side landing skid, a hook-and-release mechanism and rigging to guide the retrieval cable out the door of the helicopter. Practice trials have always been successful on the first pass.

The landing site at the Utah Test and Training Range was chosen because the area is a vast, unoccupied salt flat controlled by the U.S. Army and Air Force. The landing footprint for the sample return capsule will be about 30 by 84 kilometers (18 by 52 miles), an ample area to allow for aerodynamic uncertainties and winds that might affect the direction the capsule travels in the atmosphere. The sample return capsule will approach the landing zone on a heading of approximately 122 degrees on a northwest to southeast trajectory. Landing is planned to take place at 9 a.m. local time.

Sample Allocation and Curation

Following recovery, the canister containing the collector arrays and the concentrator will be taken to the receiving and curatorial facility at Johnson Space Center (JSC), the designated NASA Center for curation of extraterrestrial materials.

The Canister was cleaned and the Collector Arrays and Concentrator integrated in a new Class 10 cleanroom at JSC (background for Figure 5) built specifically for the Genesis mission. Post-recovery operations will be carried out in this same facility. Inasmuch as possible, the contamination control procedures during canister disassembly will be identical to those used in canister assembly. In addition, systematic, archeological-style inspection of the returned materials and components will be carried out to determine what actually happened during exposure. Based on visual inspection, any new surface marks, specifically locations of micrometeorite impacts, will be documented.

Upon receipt of the canister at JSC the transport container will be opened in a class 10,000 area. The exterior of the science canister will be wiped down with solvent until visibly clean prior to introducing the canister into the class 100 sample extraction area. Additional cleaning techniques may be used depending on the condition of the canister. The science canister will be opened in the class 100 facility and the condition of the canister interior will be described and imaged.

The disassembled collectors and concentrator target materials will be handled in air in the class 10 cleanroom conditions and stored in a dust-free, contaminant-free, high purity nitrogen environment. The collector and target surfaces will be protected from all physical contact and from static electric charging. For the specific case of Si wafers, well defined handling procedures developed by the semiconductor industry have been adapted to our needs. Procedures for subdividing individual collectors for allocation without significant contamination are being devised and tested by JSC in consultation with the Science Team.

Before allocation, the samples will be examined for factors that might affect end-use analyses, and results of those examinations will be a part of the documentation associated with each sample. The locations of the samples and the investigators to whom they are allocated will be known at all times. These data will be readily available and secure.

Overview of Plans for Sample Analysis

The opportunity to analyze returned solar wind samples will be open to the international planetary materials community as soon as possible after recovery. Allocations will be made after careful review of the proposed analytical procedures by a mission-independent Sample Allocation Committee (SAC). It is also desirable to have a focused and timely product of the mission. As we are confident that several of the important science objectives can be realized relatively quickly without compromising science quality, four studies -- N isotopes, noble gas isotopes in bulk solar wind, C isotopes, and a search for radioactive nuclei -- will be set aside to be performed by the Genesis Co-Investigators as an Early Science Return. These Early Science Return measurements were selected on the basis of a combination of science importance and feasibility. Less than 1% of the returned sample from the canister will be used in these studies.

Materials for study will be provided by the Curatorial Facility of the Johnson Space Center based on recommendations of the SAC. This process follows well-developed procedures with deep heritage going back to Apollo lunar sample allocations. In addition to SAC operation, these procedures cover the selection of SAC members, the frequency of meetings, etc. The SAC also serves as a monitoring and advisory committee to the JSC Curatorial Facility on issues relating to minimizing contamination during the handling and storage of collector materials.

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Table 1 Estimated Composition of Bulk Solar Wind (1)

Z	Element	Solar system abund. (Note 2)	Solar wind flux ($cm^{-2}s^{-1}$)	2-yr. Fluence (cm^{-2})	ppma (Note 3)	ppmw (Note 4)
3	Li	5.7E+01	1.7E+00	1.1E+08	2.2E-04	5.3E-05
4	Be	7.3E-01	2.2E-02	1.4E+06	2.8E-06	8.9E-07
5	B	2.1E+01	6.4E-01	4.0E+07	8.0E-05	3.1E-05
6	C	1.0E+07	1.0E+05	6.3E+12	1.3E+01	5.4E+00
7	N	3.1E+06	3.1E+04	2.0E+12	3.9E+00	2.0E+00
8	O	2.4E+07	2.4E+05	1.5E+13	3.0E+01	1.7E+01
9	F	8.4E+02	8.4E+00	5.3E+08	1.1E-03	7.2E-04
10	Ne	3.4E+06	3.4E+04	2.2E+12	4.3E+00	3.1E+00
11	Na	5.7E+04	1.7E+03	1.1E+11	2.2E-01	1.8E-01
12	Mg	1.1E+06	3.2E+04	2.0E+12	4.1E+00	3.5E+00
13	Al	8.5E+04	2.5E+03	1.6E+11	3.2E-01	3.1E-01
14	Si	1.0E+06	3.0E+04	1.9E+12	3.8E+00	3.8E+00
15	P	1.0E+04	2.1E+02	1.3E+10	2.6E-02	2.9E-02
16	S	5.2E+05	1.0E+04	6.5E+11	1.3E+00	1.5E+00
17	Cl	5.2E+03	5.3E+01	3.3E+09	6.7E-03	8.3E-03
18	Ar	1.0E+05	1.0E+03	6.4E+10	1.3E-01	1.7E-01
19	K	3.8E+03	1.1E+02	7.1E+09	1.4E-02	2.0E-02
20	Ca	6.1E+04	1.8E+03	1.2E+11	2.3E-01	3.3E-01
21	Sc	3.4E+01	1.0E+00	6.5E+07	1.3E-04	2.1E-04
22	Ti	2.4E+03	7.2E+01	4.5E+09	9.1E-03	1.5E-02
23	V	2.9E+02	8.8E+00	5.5E+08	1.1E-03	2.0E-03
24	Cr	1.4E+04	4.0E+02	2.6E+10	5.1E-02	9.4E-02
25	Mn	9.6E+03	2.9E+02	1.8E+10	3.6E-02	7.1E-02
26	Fe	9.0E+05	2.7E+04	1.7E+12	3.4E+00	6.8E+00
27	Co	2.2E+03	6.7E+01	4.3E+09	8.5E-03	1.8E-02
28	Ni	4.9E+04	1.5E+03	9.3E+10	1.9E-01	3.9E-01
29	Cu	5.2E+02	1.6E+01	9.9E+08	2.0E-03	4.5E-03
30	Zn	1.3E+03	3.8E+01	2.4E+09	4.8E-03	1.1E-02
31	Ga	3.8E+01	1.1E+00	7.2E+07	1.4E-04	3.5E-04
32	Ge	1.2E+02	3.6E+00	2.3E+08	4.5E-04	1.2E-03
33	As	6.6E+00	2.0E-01	1.2E+07	2.5E-05	6.6E-05
34	Se	6.2E+01	1.9E+00	1.2E+08	2.4E-04	6.6E-04

35	Br	1.2E+01	1.2E-01	7.3E+06	1.5E-05	4.2E-05
36	Kr	4.5E+01	4.5E-01	2.8E+07	5.7E-05	1.7E-04
37	Rb	7.1E+00	2.1E-01	1.3E+07	2.7E-05	8.2E-05
38	Sr	2.3E+01	7.0E-01	4.4E+07	8.9E-05	2.8E-04
39	Y	4.6E+00	1.4E-01	8.8E+06	1.8E-05	5.6E-05
40	Zr	1.1E+01	3.4E-01	2.2E+07	4.3E-05	1.4E-04
41	Nb	7.0E-01	2.1E-02	1.3E+06	2.6E-02	8.7E-06
42	Mo	2.5E+00	7.6E-02	4.8E+06	9.7E-06	3.3E-05
44	Ru	1.9E+00	5.6E-02	3.5E+06	7.0E-06	2.5E-05
45	Rh	3.4E-01	1.0E-02	6.5E+05	1.3E-06	4.8E-06
46	Pd	1.4E+00	4.2E-02	2.6E+06	5.3E-06	2.0E-05
47	Ag	4.9E-01	1.5E-02	9.2E+05	1.8E-06	7.1E-06
48	Cd	1.6E+00	4.8E-02	3.0E+06	6.1E-06	2.4E-05
49	In	1.8E-01	5.5E-03	3.5E+05	7.0E-07	2.9E-06
50	Sn	3.8E+00	1.1E-01	7.2E+06	1.4E-05	6.1E-05
51	Sb	3.1E-01	9.3E-03	5.8E+05	1.2E-06	5.1E-06
52	Te	4.8E+00	1.4E-01	9.1E+06	1.8E-05	8.3E-05
53	I	9.0E-01	1.8E-02	1.1E+06	2.3E-06	1.0E-05
54	Xe	4.7E+00	4.7E-02	3.0E+06	6.0E-06	2.8E-05
55	Cs	3.7E-01	1.1E-02	6.9E+05	1.4E-06	6.7E-06
56	Ba	4.5E+00	1.3E-01	8.5E+06	1.7E-05	8.3E-05
57	La	4.5E-01	1.3E-02	8.4E+05	1.7E-06	8.3E-06
58	Ce	1.1E+00	3.4E-02	2.2E+06	4.3E-06	2.1E-05
59	Pr	1.7E-01	5.0E-03	3.2E+05	6.3E-07	3.2E-06
60	Nd	8.3E-01	2.5E-02	1.6E+06	3.1E-06	1.6E-05
62	Sm	2.6E-01	7.7E-03	4.9E+05	9.8E-07	5.2E-06
63	Eu	9.7E-02	2.9E-03	1.8E+05	3.7E-07	2.0E-06
64	Gd	3.3E-01	9.9E-03	6.2E+05	1.2E-06	7.0E-06
65	Tb	6.0E-02	1.8E-03	1.1E+05	2.3E-07	1.3E-06
66	Dy	3.9E-01	1.2E-02	7.5E+05	1.5E-06	8.6E-06
67	Ho	8.9E-02	2.7E-03	1.7E+05	3.4E-07	2.0E-06
68	Er	2.5E-01	7.5E-03	4.7E+05	9.5E-07	5.6E-06
69	Tm	3.8E-02	1.1E-03	7.2E+04	1.4E-07	8.6E-07
70	Yb	2.5E-01	7.4E-03	4.7E+05	9.4E-07	5.8E-06
71	Lu	3.7E-02	1.1E-03	6.9E+04	1.4E-07	8.7E-07
72	Hf	1.5E-01	4.6E-03	2.9E+05	5.8E-07	4.2E-06
74	W	1.3E-01	4.0E-03	2.5E+05	5.0E-07	3.3E-06

75	Re	5.2E-02	1.6E-03	9.8E+04	2.0E-07	1.3E-06
76	Os	6.8E-01	2.0E-02	1.3E+06	2.6E-06	1.7E-05
77	Ir	6.6E-01	2.0E-02	1.3E+06	2.5E-06	1.7E-05
78	Pt	1.3E+00	4.0E-02	2.5E+06	5.1E-06	3.5E-05
79	Au	1.9E-01	5.6E-03	3.5E+05	7.1E-07	5.0E-06
80	Hg	3.4E-01	6.7E-03	4.3E+05	8.7E-07	6.1E-06
81	Tl	1.8E-01	5.5E-03	3.5E+05	6.9E-07	5.1E-06
82	Pb	3.2E+00	9.4E-02	6.0E+06	1.2E-05	8.8E-05
83	Bi	1.4E-01	4.3E-03	2.7E+05	5.5E-07	4.0E-06
90	Th	3.4E-02	1.0E-03	6.3E+04	1.3E-07	1.1E-06
92	U	9.0E-03	2.7E-04	1.7E+04	3.4E-08	2.9E-07

Entries are based on a H flux of 3 x 10^8/cm^2sec and a solar wind Si/H ratio of 1 x 10^{-4}. Solar wind abundances for all other elements are calculated by assuming that the relative solar abundances from Anders and Grevesse (1989).

Note 1: Entries in this table refer to unconcentrated bulk solar wind.

Note 2: Solar system abundance relative to Si = 10^6

Note 3: Solar wind concentration averaged over the outer 100 nm of the collector (assumed to be Si) in units of parts per million by number; i.e., (number of solar wind atoms x 10^6)/ (atoms of silicon).

Note 4: Solar wind concentration averaged over the outer 100 nm in units of parts per million by weight; i.e., (grams of solar wind element x 10^6)/(grams of silicon)

Table 2.
Precision and Accuracy of Elemental and Isotopic Analyses.

Elemental Accuracy (2σ limits) = ±10% of the number of atoms of each element per cm^2 on the collector materials

Isotopic Precision (2σ limits on the abundance ratios of the different isotopes of an element compared to a terrestrial reference standard)

C and N	±0.4%
O and Ti	±0.1%
Others ±1%	

A special effort will be made to measure the rare gas isotopes, and the abundant ones will be measured to much better than 1%. However, 1% may not be achievable for ^{124}Xe, ^{126}Xe, and ^{78}Kr.

Figure Captions

Figure 1 The Genesis spacecraft trajectory from Earth to L1 and return. The Earth-L1 distance is about 10^6 km. The lunar orbit is shown for scale. Arrows indicate the outbound and return trajectories. There are 5 "halo" orbits about L1. The large loop behind the Earth on the return trajectory positions the spacecraft for daylight re-entry.

Figure 2 An oversimplified, schematic view of measured O isotopic variations in solar system materials. An absolute value scale is used to indicate the size of the quantities that must be measured. Absolute abundances are not accurately known, but relative values among different materials can be very precisely measured, in many cases down to ±0.1%, 2 sigma. On the scale of this figure, the Earth, Moon and Mars are close, but the range of asteroidal materials, as derived from meteorite analyses, is quite large. The largest variations are found in meteoritic Ca-Al-rich inclusions (CAIs). As indicated, the uncertainties in spacecraft or spectroscopic O isotope measurements are larger than the scale of the Figure, whereas the projected Genesis precision, shown as ± 4 sigma for visibility, can resolve various theories as to the location of the solar O isotopic composition. The point labelled SM is a model prediction for the location of the solar isotopic composition.

Figure 3 Summary of N isotopic compositions in solar system reservoirs. Meteoritic $^{15}N/^{14}N$ ratios may be affected by the presence of pre-solar materials; however, even excluding these, a 60% range among different materials is observed which is unexplained. The terrestrial atmosphere may be affected by atmospheric loss increasing $^{15}N/^{14}N$. Lunar N isotopic variations, traditionally regarded as reflecting solar wind, have been a long term mystery but there is a suggestion that materials exposed on the lunar surface > 10^9 years ago has lower $^{15}N/^{14}N$. There is rough consistency between the ancient terrestrial atmosphere, minimum lunar, and Jovian atmospheric $^{15}N/^{14}N$ that would suggest that the solar $^{15}N/^{14}N$ should be 20-40% lower than the present terrestrial atmosphere, but this is totally contradicted by the SOHO solar wind result which, despite large errors, has a significantly higher $^{15}N/^{14}N$. The indicated Genesis (2 sigma) precision will closely constrain models for the variations.

Figure 4 The Genesis instruments are highly integrated towards the focused mission goal of solar wind sample return.. The Monitors, electron and ion electrostatic analyzers (Barraclough et al., 2002), yield electron and ion spectra and angular distributions which are used to identify autonomously the prevailing solar wind regime by a Solar Wind Algorithm (Neugebauer et al., 2002). The Algorithm processes the monitor data and then, via the spacecraft Command and Data Handling System, unshades the appropriate specific regime collector array, referred to as "Passive Collectors" in the Figure. The Algorithm also adjusts the voltages on the Concentrator (Nordholt et al., 2002; Wiens et al., 2002) to optimize collection efficiency. Finally, in common with all Sample Return missions, completion of science objectives requires a complement of Laboratory Analytical Instruments which are not launched.

Figure 5 One of the Collector Arrays at the end of integration. This array consists of 54 hexagons, approximately 10 cm point-to-point. The hexagons are made of different collector materials (Jurewicz et al., 2002), optimized for specific measurement objectives . The surfaces are highly polished, resulting in many reflections from objects in the room. To maintain the maximum degree of surface cleanliness for the collector materials, the collector arrays were integrated in a new class 10 clean room at JSC, as can be seen in the background of this figure as well as Figures 4 and 5.

Figure 6 Under class 10 clean room conditions, the Collector Arrays and Concentrator are integrated into a Canister. The Canister preserves the cleanliness of the collector materials. After functional testing, the Canister Cover was closed in the clean room and not re-opened until ready to collect solar wind at L1. The locations of the Fixed Array in the Canister Cover and the Deployable Array stack show clearly in this image. In flight, one of the three lower arrays in the stack is "unshaded", to provide an independent sample of a given solar wind regime. The selection of the regime and deployment of the arrays is done autonomously, based on data from the Monitors.

Figure 7 A closer view of the concentrator and Deployable Array stack in the deployed configuration. To sample a given solar wind regime, one of the three lower arrays in the stack is unshaded by rotating back in the direction of the Concentrator. The rotation is accomplished by motors (not shown) activating the Array Deployment Mechanism. When the Deployable Arrays are stowed and the Canister Cover closed, the array stack is held securely at two additional points besides the Array Deployment Mechanism shaft: (1) the Fixed Saddle fastened to the canister base as shown here and (2) the Deployable Saddle in the Canister Cover, as shown in Figure 6. After the cover is closed, the Deployable Saddle rotates out from its housing in the cover to clamp the arrays. Finally the Lock Ring is activated to seal the Canister Cover and Base. When the arrays are deployed, two additional areas in the canister are exposed to the solar wind. A Au foil collector can be seen in the lower center of the figure. A polished Al collector can be seen between the Concentrator and the Fixed Saddle.

Figure 8 Two views of the Genesis spacecraft, as seen from the Sun (upper) and from the Earth (lower). The overall flight system consists of the Sample Return Capsule (SRC) which houses the Canister and Collector Materials (Figures 3-5), a flat spacecraft deck on which the Monitors and most of the engineering subsystems are mounted, and the solar arrays. The SRC is shown in the closed configuration present just after launch or just prior to re-entry. While at L1, the Sun-facing backshell opens to expose the Canister. Figure taken from Hong et al. (2002; C 2002 IEEE))

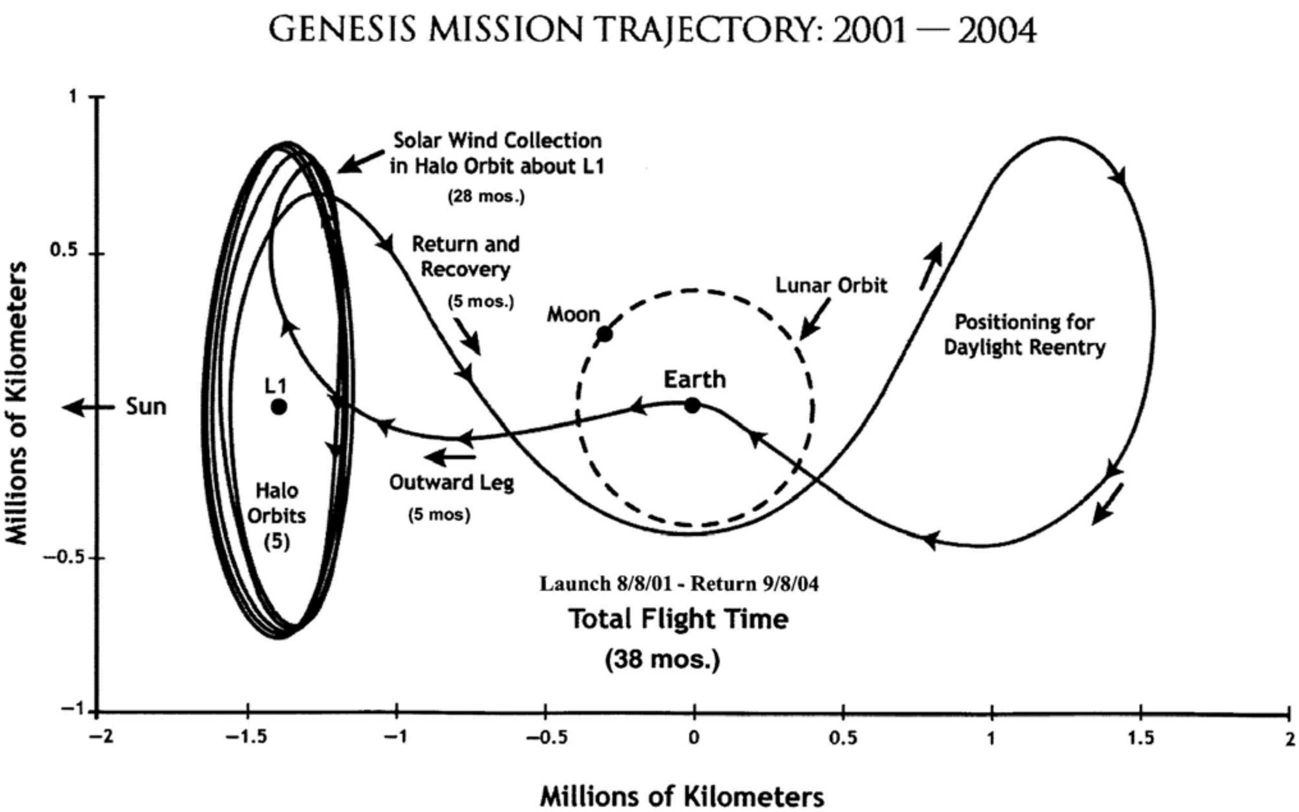

GENESIS MISSION TRAJECTORY: 2001 — 2004
Solar Wind Collection in Halo Orbit about L1
(28 mos.)
Return and Recovery
(5 mos.)
Moon
Lunar Orbit
Positioning for Daylight Reentry
Earth
L1
Sun
Halo Orbits
(5)
Outward Leg
(5 mos)
Launch 8/8/01 - Return 9/8/04
Total Flight Time
(38 mos.)
Millions of Kilometers
Millions of Kilometers
1
0.5
−0.5
−1
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2

Figure 1

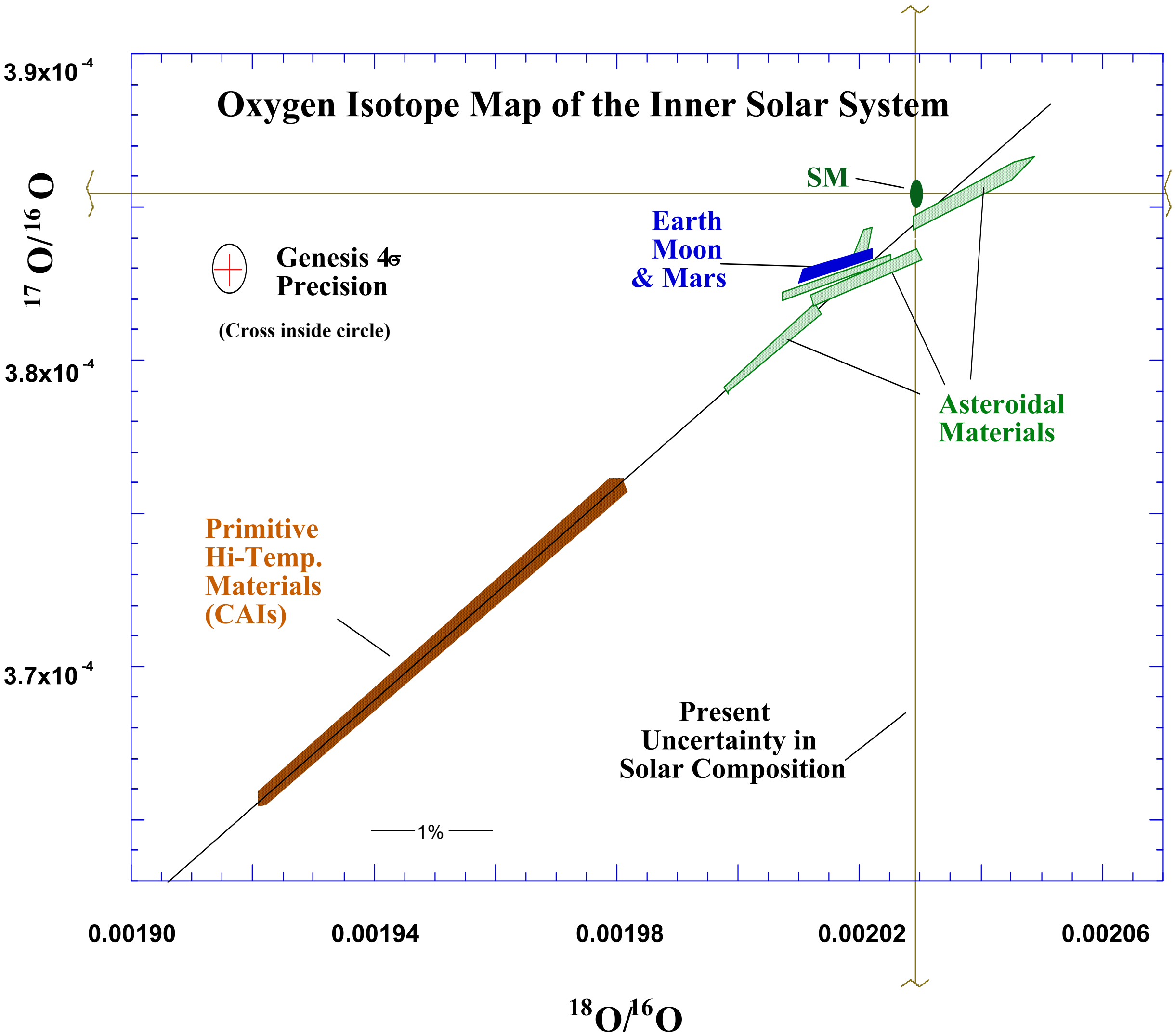

Oxygen Isotope Map of the Inner Solar System
3.9x10-4
3.8x10-4
3.7x10-4
17 O/16 O
SM
Earth
Moon
& Mars
Genesis 4σ
Precision
(Cross inside circle)
Asteroidal
Materials
Primitive
Hi-Temp.
Materials
(CAIs)
Present
Uncertainty in
Solar Composition
1%
0.00190
0.00194
0.00198
0.00202
0.00206
18O/16O

Figure 2

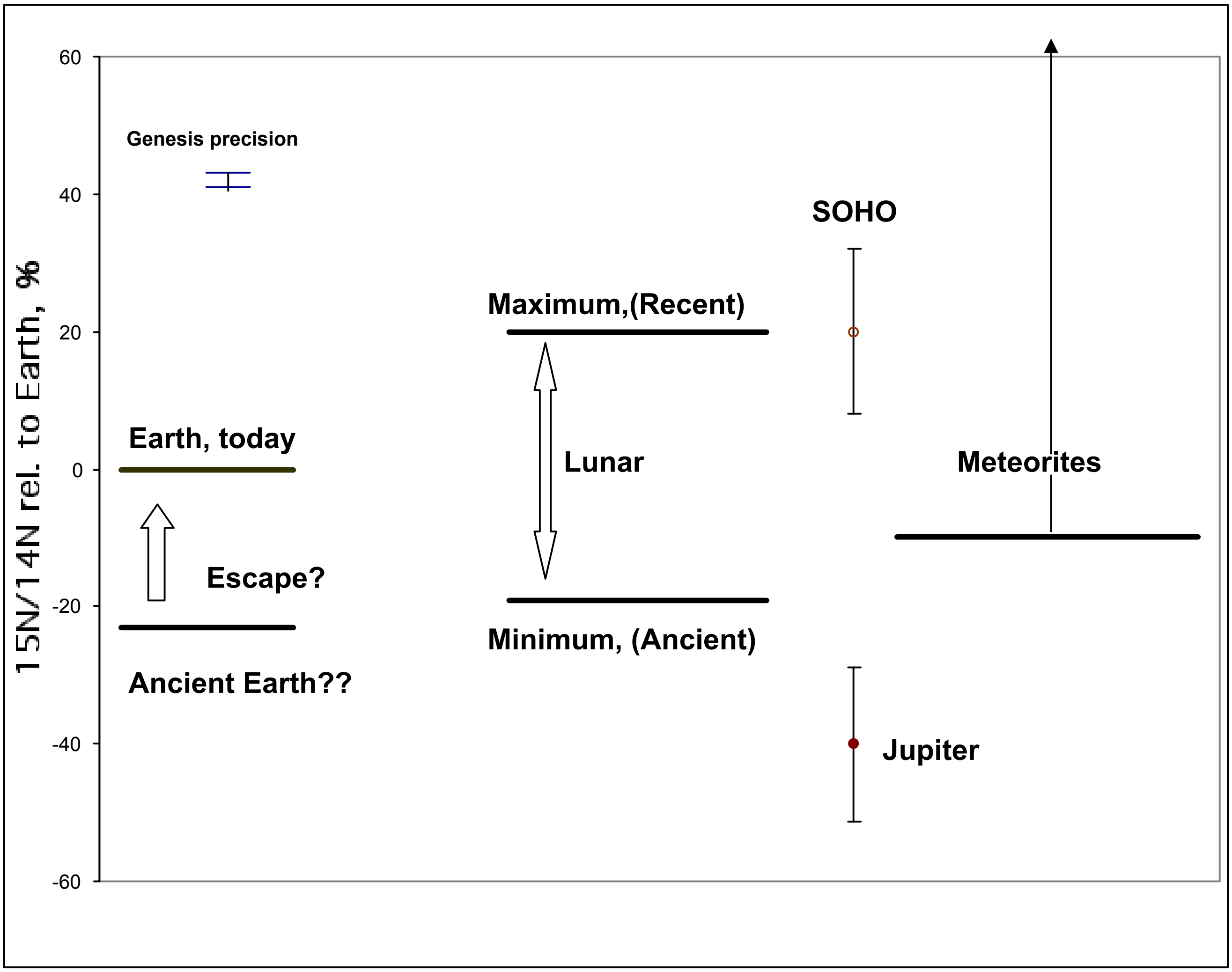

60
40
20
0
-20
-40
-60
15N/14N rel. to Earth, %
Genesis precision
SOHO
Maximum,(Recent)
Earth, today
Lunar
Meteorites
Escape?
Minimum, (Ancient)
Ancient Earth??
Jupiter

Figure 3

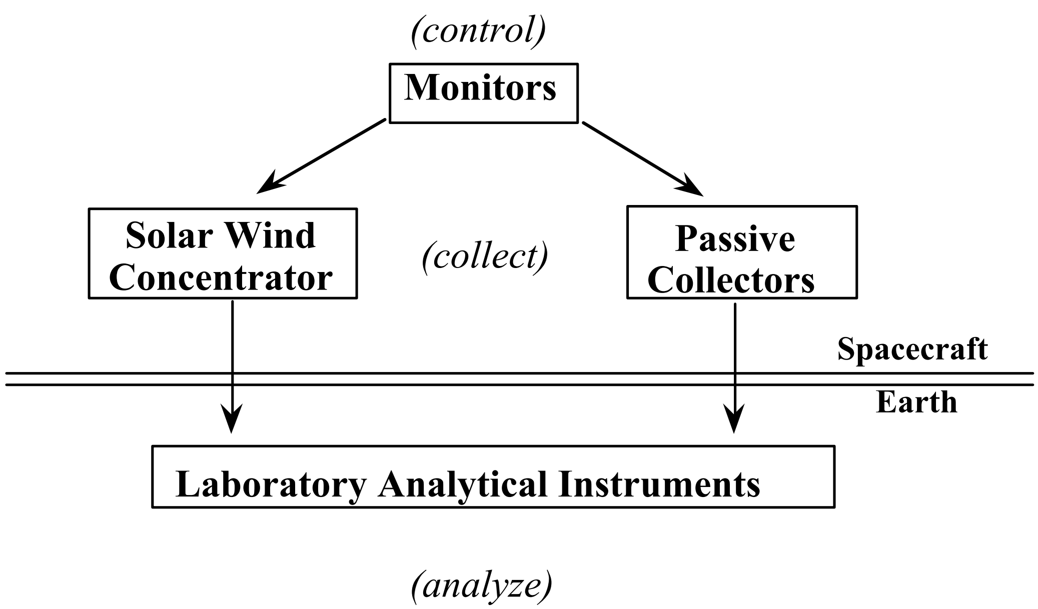

(control)
Monitors
Solar Wind
Concentrator
(collect)
Passive
Collectors
Spacecraft
Earth
Laboratory Analytical Instruments
(analyze)

Figure 4

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Figure 5.

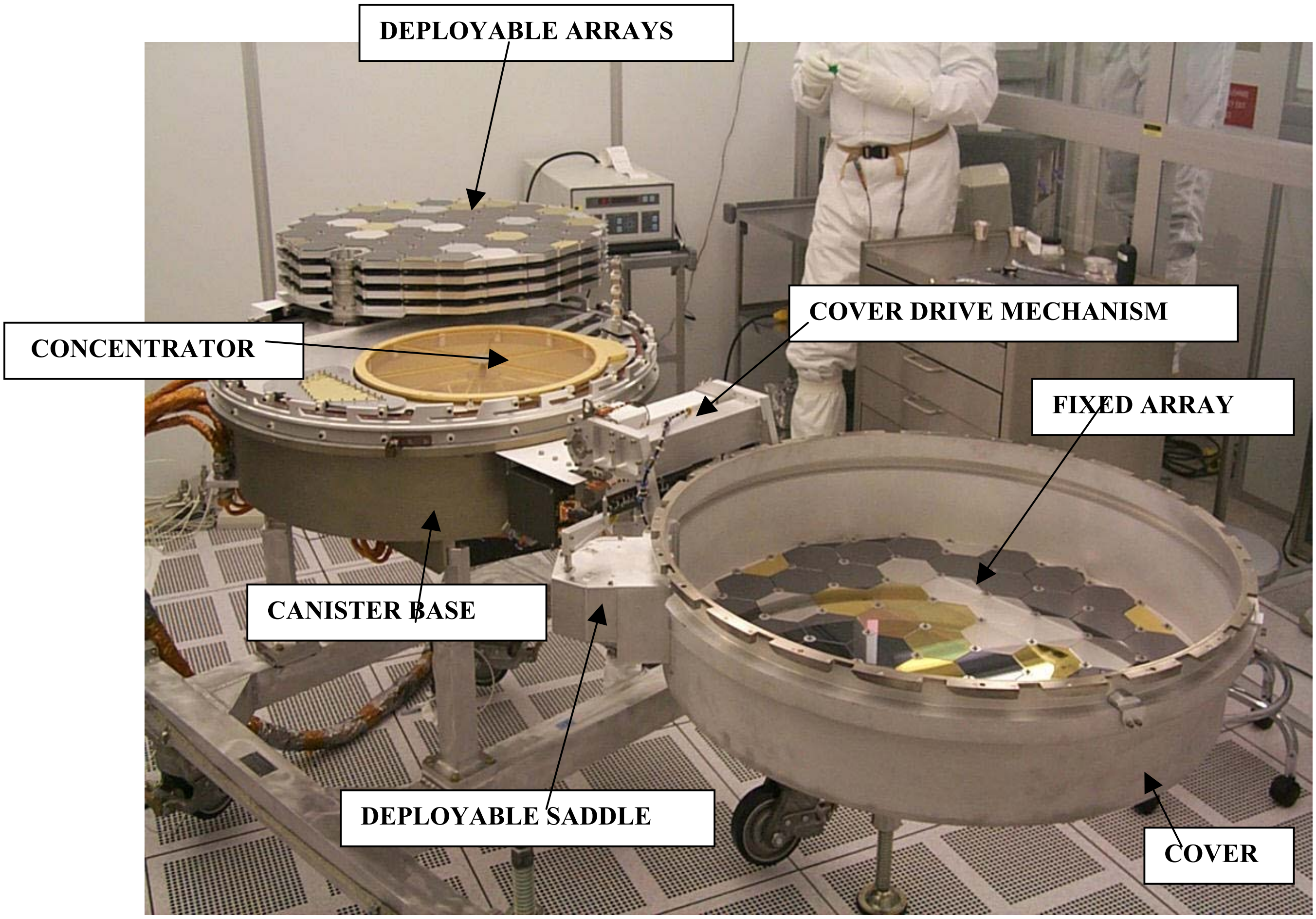

DEPLOYABLE ARRAYS
CONCENTRATOR
COVER DRIVE MECHANISM
FIXED ARRAY
CANISTER BASE
DEPLOYABLE SADDLE
COVER

Figure 6

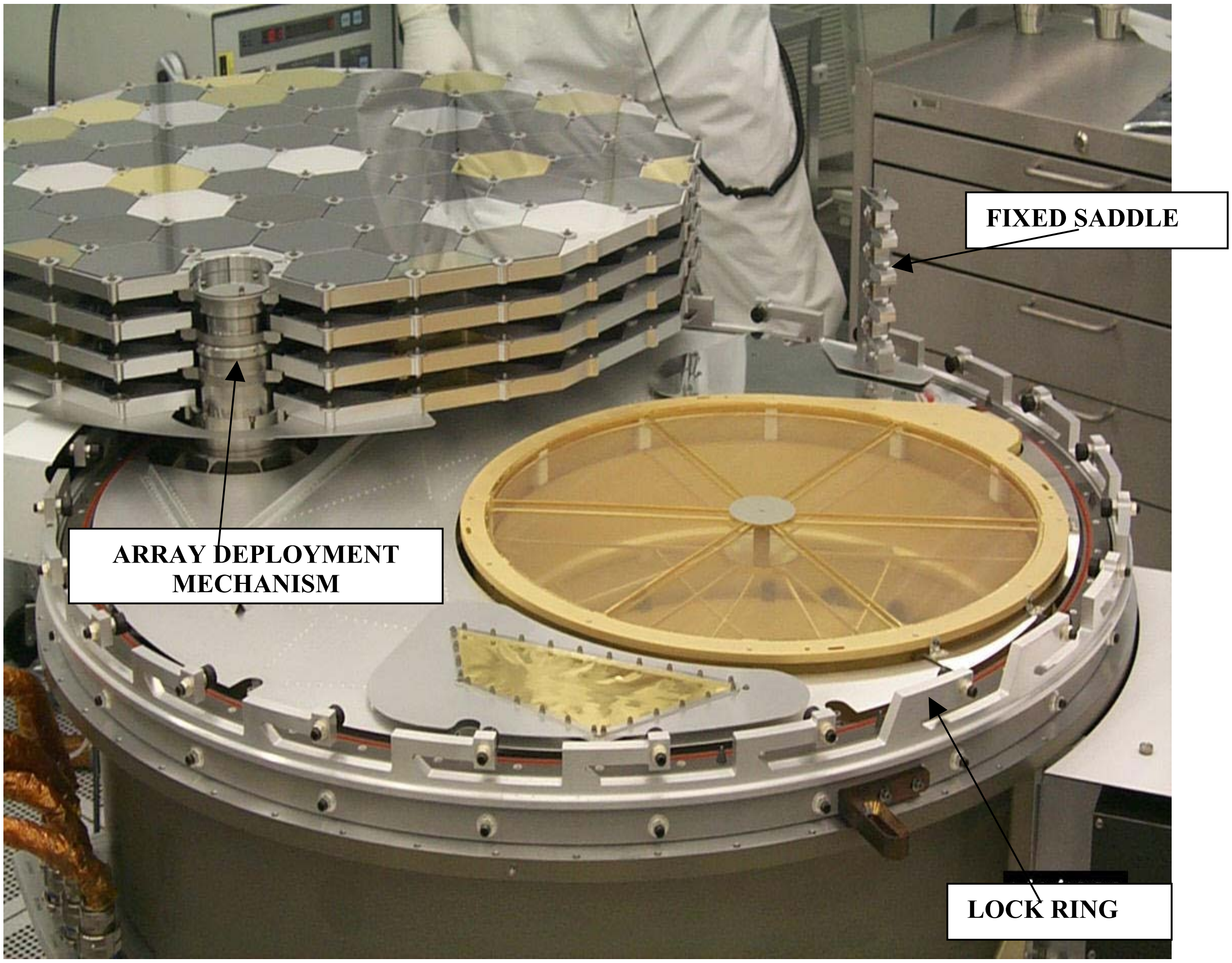
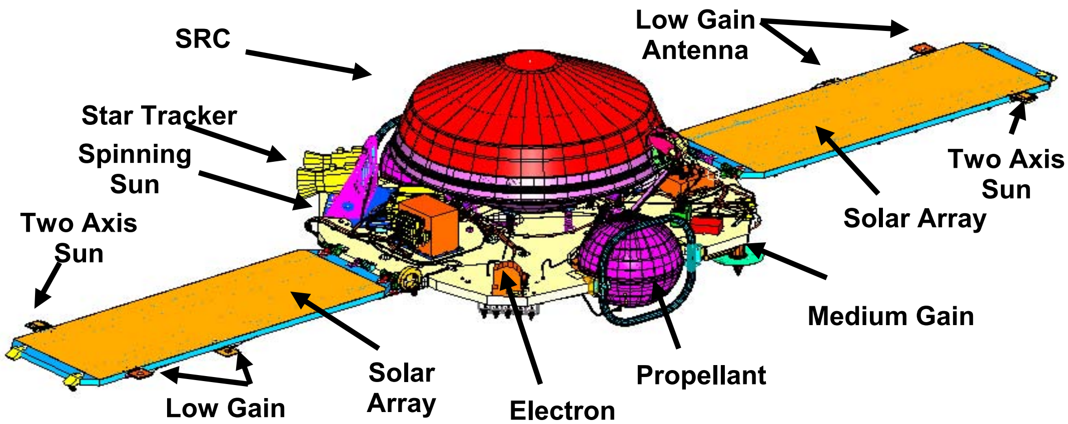


Figure 7


SRC
Low Gain
Antenna
Star Tracker
Spinning
Sun
Two Axis
Sun
Two Axis
Sun
Solar Array
Medium Gain
Solar
Array
Propellant
Electron
Low Gain

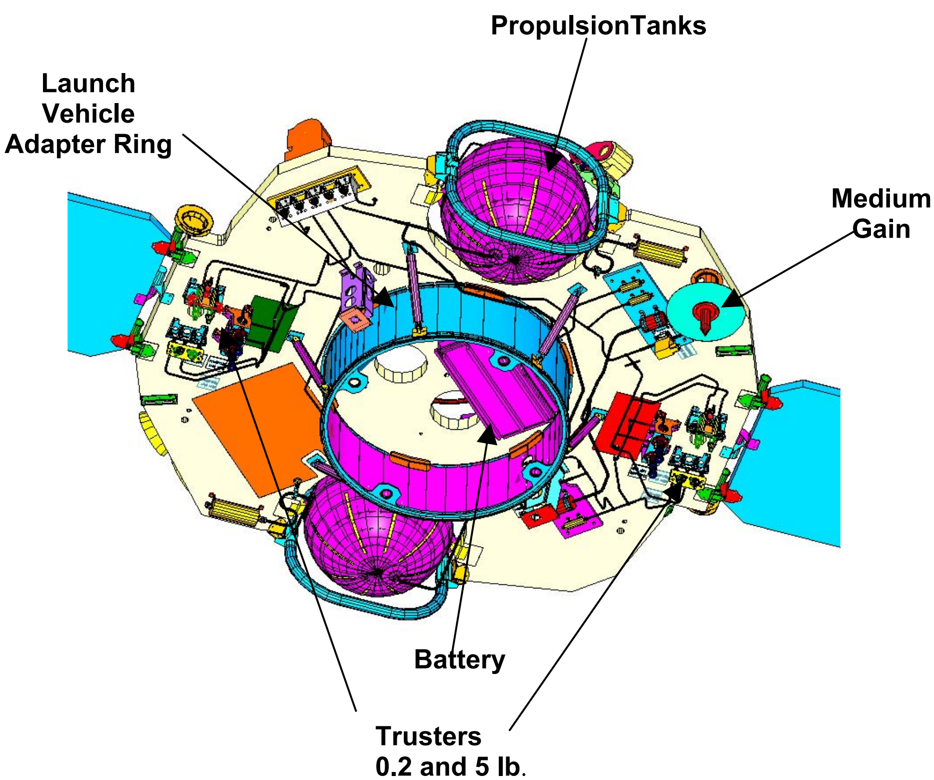

PropulsionTanks
Launch
Vehicle
Adapter Ring
Medium
Gain
Battery
Trusters
0.2 and 5 lb.

Figure 8