EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 83 NUMBER 21
21 MAY 2002
PAGES 229–240

Genesis Mission to Return Solar Wind Samples to Earth

PAGES 229, 233–234

The Genesis spacecraft, launched on 8 August 2001 from Cape Canaveral, Florida, will be the first spacecraft ever to return from interplanetary space. The fifth in NASA's line of low-cost, Discovery-class missions, its goal is to collect samples of solar wind and return them to Earth for detailed isotopic and elemental analysis. The spacecraft is to collect solar wind for over 2 years, while circling the L1 point 1.5 million km Sunward of the Earth, before heading back for a capsule-style re-entry in September 2004. After parachute deployment, a mid-air helicopter recovery will be used to avoid a hard landing. The mission has been in development over 10 years, and its cost, including development, mission operations, and initial sample analysis, is approximately $209 million.

The spacecraft is shown in Figure 1. It consists of a relatively flat spacecraft bus containing most of the subsystem components, situated below a sample return capsule that holds the solar wind collection substrates and an electrostatic solar wind concentrator. Some of the collectors are exposed throughout the collection period, for a sample of bulk solar wind, while others are exposed only to certain solar wind regimes, or types of flow. Ion and electron spectrometers feed raw data to the spacecraft control and data-handling unit, which determines ion moments and electron flux geometries in real time. An algorithm is used to robotically decide between interstream (IS), coronal hole (CH), and coronal mass ejection (CME) regimes, and to control deployment of the proper arrays to sample these wind regimes independently. This is the first time such a solar wind decision algorithm has been used on board a spacecraft.

The Genesis science team, headed by principal investigator Donald Burnett of the California Institute of Technology, consists of approximately 20 co-investigators from universities and science centers around the country and internationally.

Why Sample Return?

The findings of the Genesis mission are expected to extend far beyond solar wind composition. The overarching goal is to understand the isotopic and elemental composition of the solar nebula from which our solar system was formed, and to use this as a baseline for comparison with present-day planetary compositions. The outer layers of the Sun are considered to be relatively unchanged since the formation of the solar nebula, with the exception of slight gravitational settling and some solar surface nuclear processes such as spallation-produced enhancements of highly depleted isotopes such as ^{19}F and ^{21}Ne. The solar wind is known to be elementally fractionated relative to the solar photosphere, but fractionation of isotopes, if it exists, is relatively minor.

The prioritized Genesis measurement objectives are given in Table 1. The highest priorities are isotopic measurements for oxygen, nitrogen, and the noble gases. The science rationale, described below, argues for very high-precision measurements of ±0.1%, at the 2σ level, particularly for the ratios of all three oxygen isotopes. High-precision measurements are also required for a number of other measurements as well. While $^{18}O/^{16}O$ has been reported for astronomical observations of the solar photosphere [*Harris et al.*, 1987] and for in-situ solar wind measurements [*Collier et al.*, 1998; *Wimmer-Schweingruber et al.*, 2001], these are only at the ~10% uncertainty level, and there are no current measurements of solar or solar wind $^{17}O/^{16}O$. The situation is similar with solar wind $^{15}N/^{14}N$, where higher-precision measurements are needed than can be obtained with in-situ instruments [e.g., *Kallenbach et al.*, 1998]. There are currently no direct solar or solar wind measurements of the heavy noble gases.

The Apollo Solar Wind Composition (SWC) measurements of the early 1970s provided early groundbreaking isotopic data on solar wind helium and neon from exposures of foils for less than 48 hours on the lunar surface.

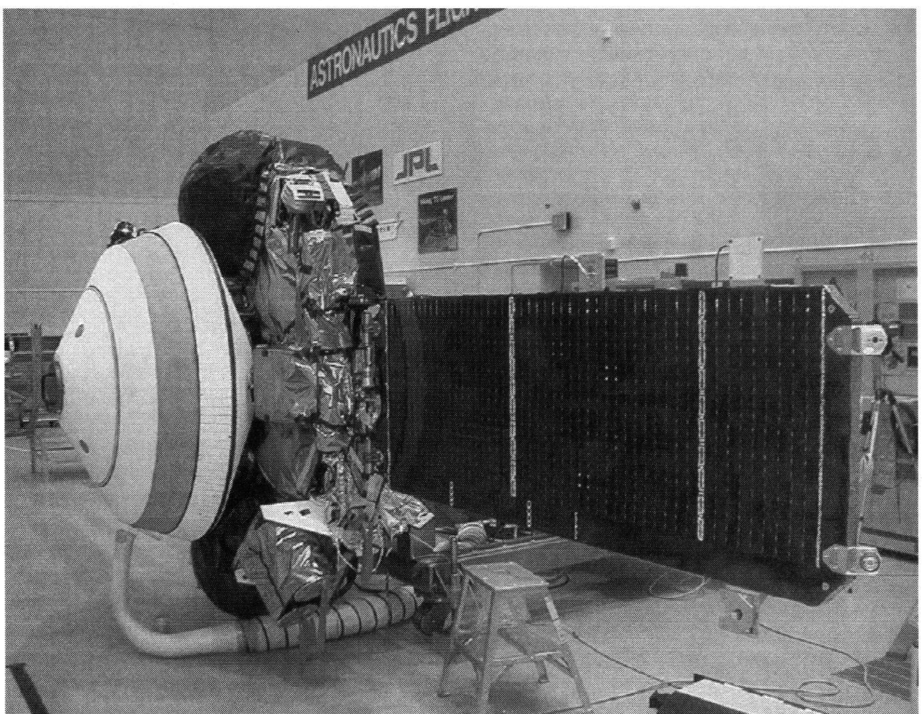

Fig. 1. The Genesis spacecraft is positioned on its side during assembly at Lockheed Martin Astronautics. The white return capsule houses all of the solar-wind collectors. The Genesis electron monitor (GEM) is the exposed instrument at the upper corner of the spacecraft deck. Original color image appears at the back of this volume.

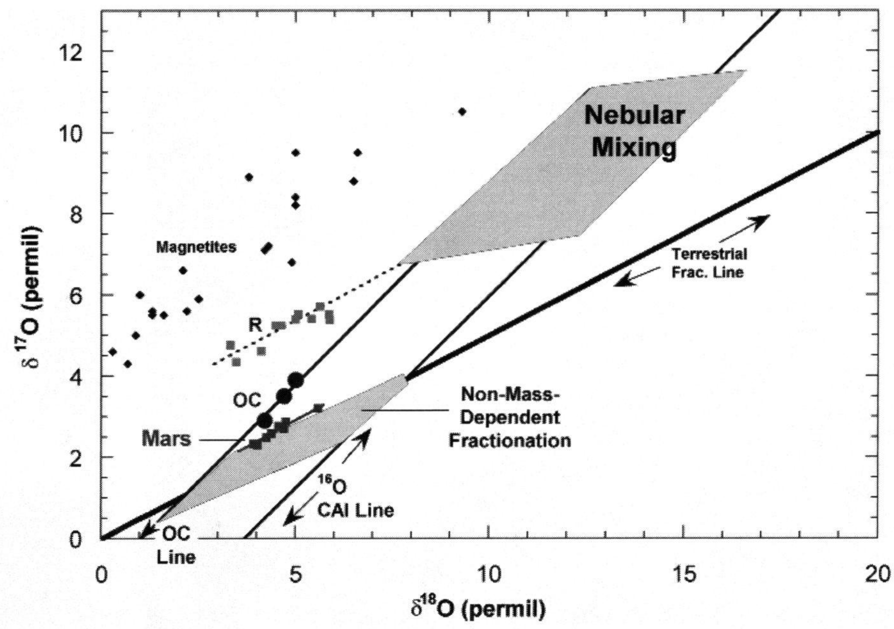

Fig. 2. This oxygen three-isotope plot shows predicted ranges (shaded) for the average solar oxygen isotopic composition based on the nebular-mixing model and the non-mass-dependent fractionation model mentioned in the text. The axes are in permil, or tenths of a percent enrichment relative to ocean water. Also shown is the Mars mixing line, based on Mars meteorite measurements, the ordinary chondrite bulk averages ("OC"), R-chondrite measurements ("R"), and individual magnetite grains measured in unequilibrated ordinary chondrites, which are thought to be derived from nebular oxygen gas (references in Wiens et al., 1999). *The "^{16}O CAI" and "OC" lines represent trends toward pure ^{16}O enrichment of high-temperature minerals in ordinary and carbonaceous chondrites. The solar $^{17}O/^{16}O$ ratio is completely unmeasured, while the present uncertainty on the $^{18}O/^{16}O$ ratio is far larger than the size of this plot. The Genesis measurement goal for oxygen is ± 1 permil, 2-σ, for both ratios.*

objectives focus on specific issues. For example, objective #9, mass 80–100 and 120–140 AMU elemental abundance patterns, is intended to understand whether the Sun preferentially accreted volatile or non-volatile elements from the solar nebula. Assuming that nebular abundances of odd-mass elements in these mass ranges follow a smooth curve based on s-process systematics, Genesis data should allow for the first time a close comparison of Kr and Xe odd isotope abundances with surrounding nonvolatile isotope abundances [e.g., *Wiens et al.*, 1991]. Likewise, measurement of Li, Be, and B elemental and isotopic abundances (objective #12) is of great importance for establishing the thermal history of the solar convective zone because the nuclear destruction of these isotopes is very temperature-sensitive. Abundances of these isotopes will likely reveal details of mixing at the base of the convective zone.

Several objectives are aimed at understanding the cumulative effect of high-energy particle interactions within the photosphere. For example, fluorine, with its very low abundance compared to surrounding elements, has likely had its initial abundance enhanced by spallation. Radioactive nuclei ^{14}C and ^{10}Be are also spallation-produced in the photosphere. Measurement of these isotopes in Genesis collection foils should give estimates of spallation near the surface of the Sun over the last several thousand to several million years, respectively. While a positive measurement is not assured, the Genesis mission will establish significantly lower limits than possible with lunar samples.

So it is clear that sample return measurements and in-situ measurements can provide very complementary data. The Genesis mission, which has both traditional plasma instruments and a significant sample return component, is a marriage between space physics and planetary science at its most basic level.

Clues to Nebular and Planetary Formation

The oxygen isotope measurements resulting from the Genesis mission are designed to distinguish between two theories about isotopic heterogeneity among planetary bodies sampled so far. Oxygen isotopes are unique in their large-scale heterogeneity of more than 6% among solar system reservoirs, which cannot be attributed to mass-dependent fractionation. One widely-held theory [e.g., *Clayton*, 1993] suggests that the solar nebula had compositionally diverse inputs of oxygen as solid-phase and gaseous oxygen components, and that incorporation of varying fractions of these components in the different solar system bodies accounts for the diversity observed today. A relatively simplistic model for this predicts the present-day solar composition to be depleted in ^{16}O relative to the bulk Earth, as shown in Figure 2 [*Wiens et al.*, 1999]. Another theory [e.g., *Thiemens and Heidenreich*, 1983] is that the oxygen isotopic diversity was produced within the hottest part of the nebula by non-mass-dependent fractionation during gas-phase reactions. Such reactions would automatically produce pure ^{16}O enrichments seen in primitive, high-temperature meteoritic objects. This theory predicts an average solar oxygen isotope composition similar to bulk Earth and Mars, as shown in Figure 2. Photospheric values may be altered slightly by gravitational settling over the solar history [e.g., *Bochsler*, 2000], but the predictions of these two theories should remain distinct. The Genesis mission should collect sufficient solar wind to allow distinction between these two predicted compositions.

Solar wind measurements of nitrogen and noble gases will aid models of planetary atmosphere formation and evolution. The original Apollo SWC measurements showed that planetary atmospheres were decisively modified by large-scale losses, as solar and terrestrial atmospheric $^{20}Ne/^{22}Ne$ differ by 30%. Atmospheric isotopic and elemental ratios still need a clear baseline for accurate hydrodynamic escape models. Estimates of solar and solar wind compositions for the heavy noble gases exist from analyses of these gases in lunar soils. However, details of their modification by implantation and diffusion processes are not completely understood. Hence, Genesis samples are anticipated for the more accurate baseline they will supply for planetary atmospheric evolution.

The lower objectives in Table 1 represent a thorough mix of astrophysics and basic planetary science. Some objectives are general "survey" measurements, but a number of

Fidelity of Solar Abundances

For elemental abundances, present estimates are generally based on two sources: photospheric emission lines and elemental abundances of primitive carbonaceous (C1) chondrite meteorites. It seems rather incongruous that solar abundances are based on meteorites, but photospheric emission lines do not exist for numerous elements; for other elements, they are uncertain enough that meteoritic abundances are considered to be more accurate. Important elements such as iron, oxygen, and beryllium have been the subject of abundance revisions of tens of percent based on recent studies of photospheric emission lines. Meteorites, on the other hand, are greatly depleted in volatile elements, and even for involatile elements, there are significant abundance differences between the several different C1 meteorites. Solar wind abundances are now available from in-situ instruments for many elements lighter than nickel. Genesis should add many more elements to the solar wind data base to provide greater understanding of solar composition.

Success in obtaining Genesis' solar composition goals will depend partly on how well the solar composition can be inferred from solar wind measurements. It is clear that solar wind is elementally fractionated relative to the photosphere as a function of the first ionization potentials (FIP). While the fractionation varies in the short term, stable long-term averages

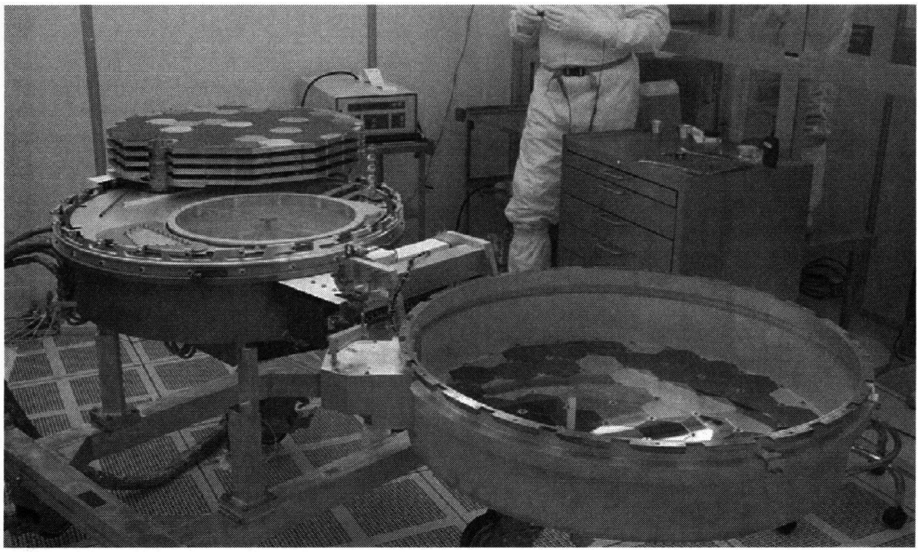

Fig. 3. The Genesis science canister is being assembled in a class-10 clean room of the Johnson Space Center, Houston, Texas. The canister is housed inside the return capsule shown in Figure 1. Collectors in the canister lid (right foreground) are always exposed when the canister is open. The top array on the stack of four (upper left) is also always exposed, while the lower three are regime-specific and only rotated out from under the top one when their solar-wind regime is identified. The solar wind concentrator is visible as the large gold instrument in the canister body. Original color image appears at the back of this volume.

Table 1. Prioritized solar-wind measurement objectives of the Genesis mission.

1. $^{16,17,18}O$ ratios to ±0.1%, 2-σ*
2. N isotopes to ±1%, 2-σ
3. Noble gas elements & isotopes, bulk solar wind
4. Noble gases in specific solar wind regimes
5. C isotopes to ±0.4%, 2-σ, bulk solar wind
6. C isotopes in specific solar wind regimes
7. Mg, Ca, Ti, Cr, Ba isotopes
8. Key first ionization potential elements
9. Mass 80–90 and 130–140 elemental abundance patterns
10. Survey of solar-terrestrial isotopic differences
11. Noble gas, N isotopes in higher energy particles
12. Li, Be, B elemental and isotopic abundances
13. Radioactive nuclei in the solar wind
14. F abundance
15. Pt-group elemental abundances
16. Key s-process heavy elements
17. Heavy-light element comparisons
18. Solar rare Earth elements abundance pattern
19. Comparison of solar and chondritic abundances

* Measurement of bulk solar wind except where noted; Elemental abundance ratios to ±10%, 2-σ

are being compiled by in-situ instruments on Ulysses, Advanced Composition Explorer (ACE), Wind, and the Solar and Heliospheric Observatory (SOHO) The fractionation factor between high and low FIP in CH wind is approximately a factor of two, while inter-stream FIP fractionation is somewhat higher.

Assuming the FIP fractionation can be well constrained by in-situ solar wind instruments for a number of elements for which photospheric abundances are already reasonably constrained by emission lines, Genesis can apply the FIP fractionation principles to obtain accurate solar abundances for many more elements. Solar wind data on elements heavier than helium show no conclusive evidence of isotopic fractionation. By comparing isotope ratios of different solar wind regimes, the Genesis mission will be the first to test, to two orders of magnitude, for long-term isotopic fractionation of heavy elements in the solar wind.

Genesis Collectors and Instruments

The Genesis payload consists of three electrostatic instruments and several square meters of solar wind collection arrays. The science canister, which contains the contamination-sensitive solar wind collectors, is shown in Figure 3. A stack of four collector arrays is deployed by rotation about a single axis. The top array is always exposed when the canister is open. The three lower arrays are regime-specific arrays. Each one is only deployed for a specific solar wind regime identified by the spectrometers and on-board algorithm, and is shaded by the stack for the remainder of the time. An array is also positioned in the lid of the canister (Figure 3). Like the top array in the stack, this one also continuously collects solar wind. In addition to canister-mounted collectors, the sample return capsule lid is covered with collection foils. For each passive collector, the solar wind ions simply embed themselves in the top 100 nm of material, awaiting analysis back on Earth.

The solar wind concentrator, mounted in the body of the canister (Figure 3), is exposed when the collectors are deployed. The concentrator provides a high-fluence sample of solar wind onto a small target. This is done specifically to increase the signal-to-background ratio for oxygen, which tends to be a ubiquitous terrestrial contaminant. The concentrator consists of a series of flat grids and a parabolic electrostatic mirror that focuses ions upward onto a collection target in the center of the instrument, like a reflecting telescope. The flat grids serve several purposes, including rejection of >90% of solar wind protons to minimize proton damage of the target, and acceleration of the remaining ions to better focus them and to allow deeper implantation in the target. The voltages of both the proton-rejection grid and the focusing mirror are continuously adjusted based on real-time ion velocity and temperature data from the ion spectrometer to optimize the performance of the concentrator. The concentrator was designed to minimize isotopic fractionation, so that the oxygen isotope precision goal of ±0.1% can still be met.

The Genesis ion monitor (GIM) and Genesis electron monitor (GEM) are typical plasma electrostatic analyzers, which provide data on proton and alpha velocities, temperatures, and densities, and electron energy and angle distributions. These instruments are mounted on opposite sides of the spacecraft deck. The GEM sensor head is an exact copy of those operating on ACE and Ulysses. GIM uses a slightly modified design from current ACE and Ulysses ion spectrometers. These instruments provide the spacecraft control and data-handling unit with complete spectra every four spacecraft rotations (every ~2.5 min). Code residing in the control and data-handling unit converts the raw GIM counts to moments, and processes GEM data to search for bi-directional electron streaming. Genesis lacks a magnetometer, so it must identify coronal mass ejections (CMEs) by a combination of bi-directional electron streaming, high alpha abundances, and high thermal mach number. Weighting functions are used so that combinations of these indicators can make the CME regime selection at the appropriate time.

As seen in Figure 3, a number of different collector materials were incorporated into the arrays, with material selection based on substrate purity and amenability to the desired analysis techniques. The bulk of the collectors are silicon wafers. Germanium wafers were also used because of their advantage with secondary ion mass spectrometry analyses. CVD diamond was included because of its low-oxygen composition and low diffusion-rate properties. A number of thin films were included: gold, silicon, aluminum, and diamond. These were mounted on sapphire wafers because of its good thermal properties and the ability to remove the solar wind-loaded films from sapphire via laser ablation. The techniques to be used for returned sample analysis include secondary ion mass spectrometry, noble gas mass spectrometry (MS), resonance ionization MS, accelerator MS, inductively coupled plasma MS, and radiochemical neutron activation analysis. These techniques have been applied to show that elemental backgrounds in the collector materials are sufficiently low, and instrumental sensitivities are sufficiently high, to analyze most elements in the solar wind, even including some of the rare-Earth elements, from a 2-year solar-wind exposure. Large collector areas and a strong curation plan will ensure the availability of solar wind samples for many years to come.

The Future of Genesis Mission

The spacecraft was inserted into its L1 halo orbit on 19 November 2001. The collector arrays were deployed and the solar wind concentrator was turned on during the first week of December. GIM and GEM have been operating since late August 2001. In addition to on-board moments and regime selection, raw plasma data are telemetered to the ground several times per week. Browse plots are made available on the Web at http://genesis.lanl.gov nearly as soon as they are downlinked, and processed data will soon be available. The Genesis L1 halo orbit is ~0.8 x 0.25 million km radius, somewhat larger than the ~0.3 x 0.2 and ~0.7 x 0.2 million km orbits of ACE and SOHO, respectively, presenting opportunities for time-resolved cluster observations of solar wind flow properties. The Genesis spectrometers will be operated at L1 until spring 2004, and then during the return phase, which takes the spacecraft through the L2 point on the tail side of the Earth prior to re-entry in September 2004. Genesis will be the first spacecraft to re-enter from beyond the orbit of the Moon, and the first spacecraft to return extraterrestrial samples in over 30 years.

Acknowledgments

We thank the thousands of people who have contributed to this mission in so many different ways. This manuscript was supported by NASA contract number 19,272.

Authors

Roger C. Wiens, Donald S. Burnett, Marcia Neugebauer, Chester Sasaki, Donald Sevilla, Eileen Stansbery, Ben Clark, Nick Smith, Lloyd Oldham, Bruce Barraclough, Eric E. Dors, John Steinberg, Daniel B. Reisenfeld, Jane E. Nordholt, Amy Jurewicz, and *Kimberly Cyr*
For additional information, contact Roger C. Wiens, Space & Atmospheric Sciences, Los Alamos National Laboratory, Los Alamos, N.M., USA; E-mail: rwiens@lanl.gov.

References

Bochsler, P., Abundances and charge states of particles in the solar wind, *Rev. Geophys.*, *38*, 247–266, 2000.

Clayton, R. N., Oxygen isotopes in meteorites, *Ann. Rev. Earth Planet. Sci.*, *31*, 115–149, 1993.

Collier, M. R., et al., Oxygen-16 to oxygen-18 abundance ratio in the solar wind observed by WIND/MASS, *J. Geophys. Res.*, *103*, 7–13, 1998.

Harris, M. J., D. L Lambert, and A. Goldman, Carbon and oxygen isotope ratios in the solar photosphere, *Mon. Not. R. Astr. Soc.*, *224*, 237–255, 1987.

Kallenbach, R., et al., Isotopic composition of solar wind nitrogen: First in-situ determination with CELIAS/MTOF spectrometer on board SOHO, *Astrophys. J.*, *507*, L185–L188, 1998.

Thiemens, M. H., and J. E. Heidenreich, III, The mass-independent fractionation of oxygen: A novel isotope effect and its possible cosmochemical implications, *Science*, *219*, 1073–1075, 1983.

Wiens, R. C., D. S. Burnett, M. Neugebauer, and R. O. Pepin, Solar-wind krypton and solid/gas fractionation in the early solar nebula, *Geophys. Res. Lett.*, *18*, 207–210, 1991.

Wiens, R. C., G. R. Huss, and D. S. Burnett, The solar oxygen-isotopic composition: Predictions and implications for solar nebula processes, *Met. Planet. Sci.*, *34*, 99–107, 1999.

Wimmer-Schweingruber, R. F., P. Bochsler, and G. Gloeckler, The isotopic composition of oxygen in the fast solar wind: ACE/SWIMS, *Geophys. Res. Lett.* *28*, 2763–2766, 2001.

Exploring Submarine Earthquake Geology in the Marmara Sea

PAGES 229, 235–236

The disastrous 1999 earthquakes in Turkey have spurred the international community to study the geometry and behavior of the North Anatolian Fault (NAF) beneath the Marmara Sea. While the area is considered mature for a large earthquake, the detailed fault geometry below the Marmara Sea is uncertain, and this prevents a realistic assessment of seismic hazards in the highly-populated region close to Istanbul.

Two geological/geophysical surveys were recently conducted in the Marmara Sea: the first in November 2000 with the R/V *Odin Finder*, and the second in June 2001 with the R/V *CNR-Urania*. Both were sponsored and organized by the Institute of Marine Geology of the Italian National Research Council (CNR), in cooperation with the Turkish Council for Scientific and Technical Research (TÜBITAK) and the Lamont-Doherty Earth Observatory of Columbia University. Multi-beam bathymetry, multi-channel seismic reflection profiling, magnetometry, high-resolution CHIRP sub-bottom profiling, and bottom imaging were carried out with a remotely operated vehicle (ROV). Over 60 gravity and piston cores were collected.

The main objectives were to identify and date fault ruptures on the sea floor, define the spatial-temporal distribution and the style of deformation and tectonic movements in this portion of a major continental strike-slip boundary, and acquire elements useful for assessing seismic hazards. Both sedimentary and topographic features that define piercing lines were studied to estimate the slip along the fault and to reconstruct the post-glacial paleo-oceanographic history of the Marmara Sea—including the effects of glacio-eustatic paleoclimatic fluctuations on the exchange between the Marmara and the Black Sea on one side, and the Mediterranean on the other. The two studies are related because detailed stratigraphy and dated morphological features such as erosional channels, submarine canyons, and paleo-shorelines can provide key markers for paleoseismology.

The major finding of this research is that the geological study of earthquakes—paleoseismology—is feasible under water. Accurate sea-bottom topography and shallow sub-bottom profiles were obtained over key portions of the eastern Marmara Sea. Faults were successfully located with an accuracy of 1–2 m. Sediment cores collected over these faults allow us to correlate disturbances in the sediment column with submarine fault activity. These data and ^{14}C datings will allow estimates of Holocene slip rates and identification of individual earthquakes on fault segments of the North Anatolian plate boundary.

The North Anatolian Fault System

The North Anatolian Fault system (NAF), one of the world's major continental transform systems, separates the Anatolian and the Eurasian plates for more than 1,600 km in northern Turkey. The motion is primarily right-lateral, with a slip rate, estimated from Global Positioning System (GPS) geodetic measurements, at approximately 24 mm/y [*McClusky et al.*, 2000]. The Marmara Sea is located near the transition between the right lateral strike-slip regime of the NAF to the east, and the extensional regime affecting most of the Aegean Sea to the west. The Marmara Sea includes three basins deeper than 1000 m that accommodate the splaying of the NAF system into several strands.

The intense seismicity of the NAF system is documented by a remarkably good record of historical earthquakes in the region [*Ambraseys and Finkel*, 1995]. A sequence of eight M>7 earthquakes has progressively ruptured this boundary from east to west during the last century. The most recent and western-most events in this sequence, the M 7.4 Kocaeli and M 7.1 Duzce main shocks of 1999, were particularly destructive. They ruptured about 160 km of this fault system, including a submarine portion in the Gulf of Izmit, eastern Marmara Sea [*Barka*, 1999; *Reilinger et al.*, 2000; *Wright et al.*, 2001]. However, little strain has been released since the mid-1700s by earthquakes along 150 km of the transform through the Marmara Sea. The segment of the NAF connecting the Gulf of Saros and the western Marmara Sea (Ganos Fault, Figure 1) ruptured in 1912; this is the only large rupture in the

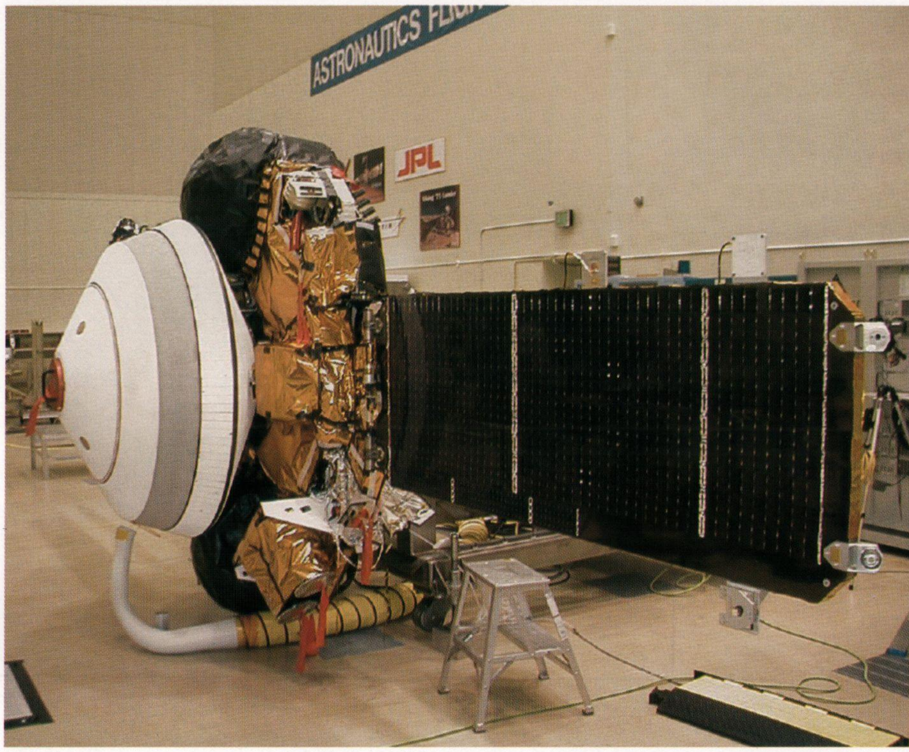

Fig. 1. The Genesis spacecraft is positioned on its side during assembly at Lockheed Martin Astronautics. The white return capsule houses all of the solar-wind collectors. The Genesis electron monitor (GEM) is the exposed instrument at the upper corner of the spacecraft deck.

Page 229

Fig. 3. The Genesis science canister is being assembled in a class-10 clean room of the Johnson Space Center, Houston, Texas. The canister is housed inside the return capsule shown in Figure 1. Collectors in the canister lid (right foreground) are always exposed when the canister is open. The top array on the stack of four (upper left) is also always exposed, while the lower three are regime-specific and only rotated out from under the top one when their solar-wind regime is identified. The solar wind concentrator is visible as the large gold instrument in the canister body.

Page 234