Galileo's epic odyssey around Jupiter. . . and the Sandia connection

By Ken Frazier

When the Galileo spacecraft plunged deep within the intense radiation belts of Jupiter again just before New Year's, mission planners marveled at this amazing spacecraft's extraordinary ability to continue to function.

Sandians had a special reason to take pride in the Labs' contributions to the mission's phenomenal success.

It was Galileo's 29th encounter with Jupiter in the five years since going into a huge, elongated orbit around Jupiter. The orbit takes the craft way out into space and then accelerates it in past the giant planet and its moons to take breathtaking close-up photos and collect and transmit priceless scientific data — all the while withstanding radiation that would instantly fry any standard electronic system.

On Dec. 28, 2000, the day that 29th orbit was completed, NASA said Galileo had already received three times the cumulative radiation exposure it was designed to withstand and was continuing to make valuable scientific observations more than three years after its original two-year mission in orbit around Jupiter. The mission has been extended twice, and is now continuing into the new millennium. Starting this month Galileo will begin transmitting images and data gathered during that most recent passage past Jupiter and its moon Ganymede.

Galileo 'very much the hero'

Galileo is the first spacecraft to orbit one of the outer planets. Launched by the space shuttle Atlantis in 1989, Galileo traveled a complicated six-year trajectory that took it twice past Earth and once around Venus for gravitational assist to finally reach Jupiter in December 1995. It was designed to function for 20 months in Jovian orbit. But Galileo has far surpassed all hopes of its designers.

The result has been one of the most successful and long-lived missions of planetary exploration ever, with new discoveries every few months about Jupiter and its moons.

"The question of the year is why [Galileo has] been able to survive three times the radiation it was supposed to," mission manager Jim Erickson said at a Dec. 30, 2000, NASA Jet Propulsion Laboratory briefing for reporters. Said another JPL manager, "For it to have survived 2-1/2 times as long as its mission length in a hazardous environment, Galileo is very much the hero here." Engineers are calling Galileo "the little spacecraft that could."

Galileo's longevity allowed a new double-whammy space-first to happen on Dec. 29. On that day, for the first time ever, two spacecraft were observing Jupiter simultaneously. One was Galileo, the other the newly arrived, just-passing-through Cassini, getting a gravitational boost from Jupiter on its way to Saturn. Galileo was supposed to be long dead by now, but, like the Energizer bunny, it just keeps going and going.

The secret of Galileo's impressive ability to function despite the Jupiter system's intense radiation? Radiation-hardened microelectronic chips supplied by Sandia.

At the request of NASA's Jet Propulsion Laboratory, Sandia supplied 10,000 specially made radiation-hardened chips to JPL for Galileo. Two thousand of them were used in the spacecraft. Sandia designed and produced the chips, drawing upon its long experience in making sure electronics for nuclear weapons can withstand intense radiation environments.

Not just any microchips

"The reason the Galileo mission went so well was because it used Sandia's radiation-hardened chips for the bit-slice processor and memory," says Dave Myers (1702), Deputy Director of Sandia's Microsystems Science, Technology, and Components Center 1700. "It's not like just any microchips would work in the Jovian radiation field."

All this happened so far back that even many veteran Sandians may barely remember it. Newer staff members may not have heard the story at all. A major space mission such as Galileo can take well over a human generation to come to fruition.

Memory and processor chips for Galileo were selected in 1977. In 1980, Sandia announced it had been selected to supply radiation-hardened versions of the chips to JPL for Galileo. The components included microprocessors, memories, and custom integrated circuits. Sandia had developed the radiation-hardening capabilities over the previous decade to ensure that nuclear weapons would continue to function in intense radiation environments.

Sandia originally intended only to develop production techniques and transfer the hardening technology to a commercial supplier to develop the chips for Galileo. But the tight time scales made that impossible. So Sandia decided it would produce the chips on site — specifically at what was then Allied Signal's Albuquerque Microelectronics Operations, on the south side of Area 1.

"The Sandia chips must function perfectly because they are the heart of systems which measure, correlate, analyze, and transmit data about the surface and atmosphere of Jupiter and its satellites," Bob Gregory, then the manager of Sandia's Microelectronics Technology Department, said in the Sandia announcement of May 2, 1980.

The next year Sandia began supplying electronic components capable of withstanding a total dose exposure of 50,000 rads.

New problem discovered late

About that same time, JPL engineers were becoming concerned about a new problem — not just total radiation dosage but damaging effects of single high-energy particles impacting a memory cell and causing damage. Several problems with the Pioneer 1 and 2 (1973 and 1974) and Voyager 1 and 2 (1979) flybys of Jupiter were now attributed to these "single-event upsets" or SEUs. Sulfur and oxygen ions from Jupiter's volcanic moon Io were being accelerated to high energy by the Jovian gravity, causing great concern.

In 1982, Galileo Project Chief Engineer Gentry Lee was assigned to determine how bad the SEU problem was and to find a solution. Cyclotron tests and analysis of the Pioneer and Voyager data showed that some of the more advanced chips planned primarily for Galileo's attitude-control system and a few others places on both the spacecraft and the atmospheric probe would be unacceptably prone to SEU. The mission's success critically depended on getting rid of the SEU problem.

As a result, in mid-1983, scientists and engineers at Sandia's Center for Radiation-hardened Microelectronics began to develop a set of brand new SEU-immune devices that would be functional, physical, and electrical replicas of the original parts. They found a way to achieve sufficient SEU immunity without sacrificing speed.

Keith Treece, Al Giddings, and Frank Hewlett, all then of the Labs' Microprocessors and Memories Division, spearheaded that effort, working under the direction of Ray Bair (ret.), then manager of Sandia's Microelectronics Products Department. Paul Dressendorfer (1732), department manager, and Ron Jones (1741), technology engineer, directed the technology development effort and were responsible for circuit fabrication and manufacture.

Sample chips were tested both at a cyclotron at Lawrence Berkeley Laboratory and in Sandia's own Gamma Irradiation Facility. The actual components had also undergone 168 hours of heat and voltage tests.

By October 1985, the full delivery to JPL — more than 10,000 radiation-resistant chips representing a major portion of the electronics to be used in the Galileo spacecraft — was complete.

Sandia's work called crucial

"Sandia's work in this area was absolutely crucial for the success of the mission," Project Galileo Director John Casani said in 1985. "SEU was not a well understood phenomenon early in the project. Sandia's quick solution to the problem avoided the necessity to develop a new computer for the spacecraft at a very late date."

Frank Hewlett, now Manager of Product Development Dept. 1737, acknowledges that he and his Sandia colleagues are pleased with the success of the Galileo mission and the Labs' role in it.

"There have been a number of occasions to celebrate, and we have done so joyously a number of times over the years," he says. "It was a good thing."

Galileo's launch was delayed several years by the explosion of the space shuttle Challenger in 1986. When it was finally launched by the space shuttle Atlantis, Oct. 18, 1989, there was great jubilation throughout the space community. At Sandia, Labs scientists and engineers again experienced quiet delight.

Galileo has now been in orbit around Jupiter for more than five years, and its discoveries and images keep coming. The little spacecraft that could has outperformed all expectations. Sandia has never been big at tooting its own horn, but all Sandians can take some pride in knowing that they and their colleagues helped make the Galileo mission the tremendous success it has become.

Radiation-hardening at core of Labs' competence in microelectronics

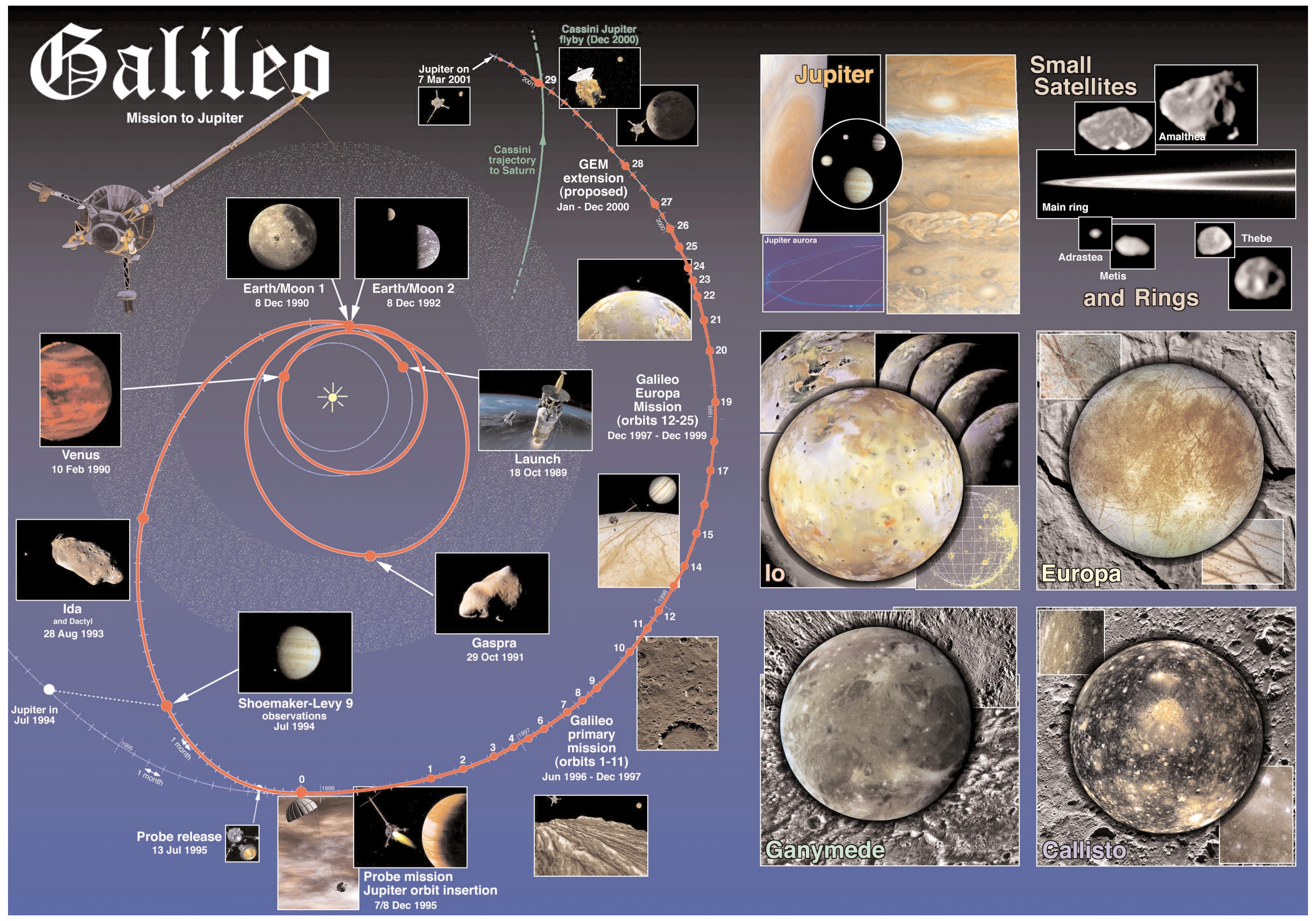
Sandia's contributions to the Galileo mission's great success "remind us that radiation-hardening is the basis of our microelectronics work, past, present, and future," says Al Romig, VP for Science, Technology, and Components Div. 1000. "People should remember that at the very core the reason for our microelectronics work is radiation-hardening."

There is "a huge synergy and interplay" between these areas, he says.

Even with the forthcoming MESA project, he says, despite all the attention about microsystems, "one of the key things we will have to deliver is radiation-hardened circuits for our national security mission and the stockpile. As a matter of fact, the W76 rebuild will have radiation-hardened parts from Sandia's Microelectronics Development Laboratory/MESA," he notes.

"It's important for us to have outside customers like NASA for our radiation-hardened capabilities," Al says. "It allows us to continue to develop new technology and sharpen and maintain our competence inside the laboratory so we can use that for the benefit of national security, especially our nuclear weapons program. Without these things, it'd be difficult to maintain our competence as well as to move forward."

David Williams, Director of Microsystems Science, Technology, and Components Center 1700, notes that future space probes to Europa, a moon of Jupiter, as well as other space missions, will need radiation-hardened Pentium chips, which could include hardened Pentium chips made in the MDL by Sandia. In December 1998, DOE, Sandia, Intel, NASA/JPL, NASA Goddard, the Air Force Research Laboratory, and the National Reconnaissance Office announced a landmark agreement in which Sandia will redesign Intel's Pentium processor into a radiation-hardened chip for defense and space uses (*Lab News*, Dec. 18, 1998).

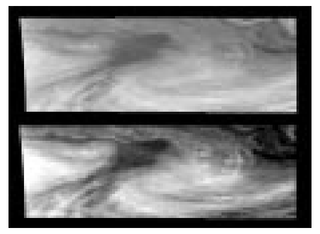


NASA'S EPIC ADVENTURE: Further information and images from the Galileo mission are available on the Web at: http://galileo.jpl.nasa.gov.

New worlds: Galileo's rich lode of discoveries about Jupiter and its four largest moons

Now you can add Jupiter's moon Ganymede, the largest moon in the solar system, to the growing list of worlds with evidence of liquid water under the surface.

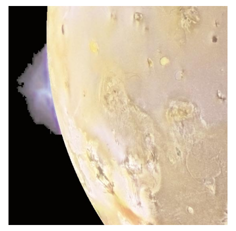
This is just the latest discovery from the Galileo mission. On Dec. 16, 2000, NASA and scientists from NASA's Jet Propulsion Laboratory, Brown University, and the German Aerospace Center reported to the American Geophysical Union that a thick layer of melted, salty water somewhere beneath Ganymede's icy crust would appear to be the best way to explain some of the magnetic readings taken by Galileo during its close approaches to Ganymede in May 2000 and earlier.



GIANT STORMS

In addition to the magnetic readings, infrared reflectance spectra obtained by Galileo as well as new photographic images from Galileo indicate that salty water may have emerged from below or melted at the surface. The images hint at how slushy ice may have surfaced through the fractured crust, much like the linear features on Europa, a neighboring moon believed likely to have a deep ocean beneath its ice.

Here are some of the other discoveries made by Galileo:



VOLCANO ON IO

• **Jupiter's Storms and Rings:** Using data from the Galileo probe's plunge into the top cloud layers of Jupiter, Galileo has discovered that Jupiter has thunderstorms many times larger than Earth's. It has also shown that Jupiter's rings are made of small dust grains blasted off the surface of Jupiter's four innermost satellites by the impacts of meteoroids.

OCEAN ON EUROPA?

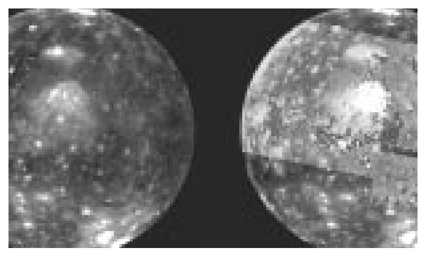
• **Hot Active Volcanoes on Io:** The Voyager mission in 1979 first discovered volcanoes on Jupiter's moon Io — now considered the most volcanic body in the solar system— but Galileo has found evidence of very hot volcanic activity on Io — hotter than in Earth's volcanoes — and observed dramatic changes compared to previous observations and even during the period of Galileo's observations.

• **Possible Ocean on Europa:** Europa appears to have had a salty ocean beneath its icy cracked and frozen surface. Galileo images show ice "rafts" the size of cities, frozen "puddles" that smooth over older cracks, and exposed evaporative- type salts. A remarkable lack of craters shows the surface to be relatively young.

GANYMEDE'S own magnetic field

• **Ganymede's Own Magnetic Field:** Galileo revealed that Ganymede has its own magnetic field. The stirring of a molten core of iron sulfide is believed to generate it.

• **Does Callisto Have a Subsurface Ocean?** Galileo has provided evidence to support the existence of a subsurface ocean on Callisto. It would have to be deep enough inside the moon that it does not affect the heavily cratered surface on top. Instead the ocean could be showing itself indirectly through the magnetic field it generates. This could come from electric flow in a salty ocean.



CALLISTO'S SUBSURFACE OCEAN?

Sandia given NASA Achievement Award in 1994 for Galileo work

In September 1994, with the Galileo spacecraft still 14 months from Jupiter, a project official came to Sandia to present the Labs with the NASA Public Service Group Achievement Award for its contributions to the Galileo mission (*Lab News*, Oct. 14, 1994).

JPL Galileo Mission Director Neal Ausman, Jr., said the Sandia components were working flawlessly.

In a ceremony in Bldg. 858, he presented the award to Sandia "for the successful development in record time of a CMOS [complementary-metal-oxide-semiconductor] replacement coprocessor and peripherals for the Galileo Attitude and Articulation Control Subsystem, thus enabling the successful mission of the spacecraft on its demanding flight to explore the Jovian system."

Even at that time, Galileo had made several discoveries. It had taken close-up images of two asteroids (Gaspra and Ida) and discovered a moon in orbit about Ida. From its special vantage point, it had also photographed the July 1994 collisions into Jupiter of Comet Shoemaker-Levy.

A Sandia/Galileo timeline

1977	Galileo spacecraft's processors and memories chosen.
May 2, 1980	Sandia announces it will produce about 12,000 radiation-hardened microelectronic components for NASA for the Galileo mission to Jupiter and another mission, the International Solar Polar Mission (later named Ulysses).
1981	Sandia engineers begin supplying electronic components for Project Galileo capable of withstanding a total dose exposure of 50,000 rads.
1982	Galileo project officials determine that single-event-upsets — errors caused by highly charged particle impacts on memory cells — are a potentially crippling problem for Galileo. They contract with Sandia to provide new chips immune to SEU events.
Mid-1983	Sandia scientists and engineers begin to develop a set of new devices immune to single-event-upsets otherwise identical to the original parts.
Oct. 1985	Delivery of 10,000 Sandia radiation-hardened chips to JPL completed.
May 1986	Originally scheduled launch date for Galileo. The space shuttle Challenger explosion, Jan. 28, 1986, delays all scheduled launches by several years.
Oct. 18, 1989	Galileo launched by space shuttle Atlantis.
Sept. 19, 1994	JPL presents Sandia with NASA Public Service Group Achievement Award, recognizing Labs' contributions to Galileo mission for design and development of CMOS coprocessor and peripherals to prevent single-event upset.
Dec. 7, 1995	Galileo goes into orbit around Jupiter. Released atmospheric probe enters Jovian atmosphere, relays data for 57 minutes, gives information on wind speeds (4,000 mph), higher-than-expected concentrations of helium, relatively dry atmosphere.
July 1996	NASA reports Galileo has returned stunning close-ups of Jupiter's moon Ganymede revealing that it has been extensively bombed by comets and asteroids and dramatically wrinkled and torn by the same forces that make mountains and move continents on Earth. "These images have exceeded our wildest expectations," says the head of the imaging team. The findings were revealed in data returned by Galileo in its first flyby of Ganymede on June 27, when the spacecraft came within just 835 kilometers (519 miles).
Dec. 1997	Galileo makes its closest flyby (124 miles) of Jupiter's icy moon Europa. This starts an extended mission focusing on new scientific questions raised by its just-completed, highly successful two-year primary mission.
Oct. 11, 1999	Galileo makes then closest pass ever to Jovian moon Io, 380 miles. Data show it is even more volcanic than expected, with more than 100 active volcanos.
Feb. 2000	Galileo passes within 124 miles of Io, returns photos of lava flows, cliffs, and depressions from collapsed volcanic eruptions.
March 8, 2000	NASA extends the Galileo mission again, called the Galileo Millennium Mission, through the end of 2000.
Aug. 2000	NASA researchers report the strongest evidence yet that one of Jupiter's most mysterious moons, Europa, hides an ocean of water underneath its icy coat. The evidence comes from magnetic readings by Galileo, reported in the Aug. 25 *Science*.
Dec. 28, 2000	Galileo completes 29th orbit of Jupiter. Flies within 310,000 miles of Jupiter's cloud tops, passing through high-radiation environment; also flies within 1,452 miles of the surface of Ganymede; images to be transmitted beginning this month (February 2001).
Dec. 29, 2000	Galileo and Saturn-bound spacecraft Cassini, passing Jupiter to get a gravitational boost, simultaneously observe Jupiter; first time two interplanetary spacecraft observe the same outer planet at the same time.
May 2001	Galileo scheduled to fly by Jovian moon Callisto.

—Timeline compiled by the Lab News *from NASA, Sandia documents*