Jupiter—At Last!

Donald J. Williams

On 7 December1995, the Galileo spacecraft arrived at Jupiter after two decades of toil and a remarkable 6-year, 3.5-billion-km journey through the solar system. This long-awaited mission to study Jupiter's atmosphere, satellites, and magnetosphere has finally begun. The 20 years taken to reach this point make Galileo the longest mission, from start (mission approval) to beginning (arrival at Jupiter), that NASA has yet conducted. This article is a perspective of the mission as viewed by the Energetic Particles Detector Team at the Applied Physics Laboratory over the history of the project—and a career-encompassing and event-filled history it has been!

INTRODUCTION

During its 6-year flight through interplanetary space from Earth to Jupiter, Galileo conducted close gravitational-assist flybys at Venus (once) and at Earth (twice), encountered two asteroids, photographed the impact of Shoemaker–Levy comet (SL9) fragments with Jupiter's atmosphere, released a probe that entered the Jovian atmosphere, received the data from that probe, and entered into orbit about Jupiter. This journey, begun at launch on 18 October 1989, is but one part of the remarkable odyssey of Galileo during which it has endured numerous program delays, the nation's worst space disaster, an ensuing lack of launch capability, a broken antenna, and a recalcitrant tape recorder. Despite this troubled history, the mission has been an outstanding success and is poised to deliver many insights about that most fascinating of solar system planets, Jupiter.

The mission is named in honor of Galileo Galilei (1564–1642), inventor of the telescope and discoverer of Jupiter's four large moons (Io, Europa, Ganymede, and Callisto), now known as the Galilean moons. APL's involvement in the Galileo mission is through the provision of a major instrument on the orbiter, the Energetic Particles Detector (EPD) (see the boxed insert). The EPD, developed jointly with the Max Planck Institute for Aeronomy, measures the energetic charged particle populations throughout Jupiter's magnetosphere. The EPD continues the APL contributions to Jovian magnetospheric research begun with instruments on the Voyager[1,2] and Ulysses[3] spacecraft. Detailed results from the EPD will be reported in a future issue of the *Technical Digest*. We now briefly describe the mission, the journey to Jupiter, some results gathered on the way, its arrival at Jupiter, and future expectations.

THE MISSION

Jupiter, the fifth planet from the Sun and first signpost of the outer solar system, is the target of the Galileo mission (Fig. 1). It is located an average distance of 5.2 AU from the Sun (1 AU is the average distance of Earth from the Sun, 150 million km) and takes 11.9 Earth-years to complete one circuit around the Sun. At its closest distance to Earth, the one-way light travel time is 35 min. A giant gaseous planet, it

THE GALILEO ENERGETIC PARTICLES DETECTOR

   Among its complement of particles and fields instruments, the Galileo spacecraft carries the Energetic Particles Detector (EPD) designed to measure the characteristics of particle populations important in determining the size, shape, and dynamics of the Jovian magnetosphere. To make the necessary measurements, the EPD provides 4π angular coverage and spectral measurements for $Z \geq 1$ ions from 20 keV to 55 MeV, for electrons from 15 keV to >11 MeV, and for the elemental species helium through iron from approximately 10 keV/nucleon to 16 MeV/nucleon. Two bidirectional telescopes, mounted on a stepping platform, use magnetic deflection, energy loss versus energy, and time-of-flight techniques to provide 64 rate channels and pulse height analysis of priority selected events. The EPD data system provides many possible operational modes from which a small number will be selected to optimize data collection during the many encounter and cruise phases of the mission. The EPD uses several safing algorithms when self-checking procedures indicate a problem. The EPD has demonstrated its operational flexibility throughout the Galileo program by readily accommodating an evolving mission profile, such as the Venus flyby, the Earth-1 and -2 encounters, the asteroid encounters, and the new low-data-rate operations at Jupiter. To date, the EPD performance in flight has been nominal.

(a)

(b)

(c)

(d)

The Galileo Energetic Particles Detector (EPD). (a) Photograph of the EPD with its protective covers open as they are in flight. (b) Schematic of the EPD showing the mounting of the detector telescopes on a stepper motor platform. Motion of the platform coupled with the spacecraft spin allows measurements in all directions. The two telescopes are (c) the low-energy magnetospheric measurement system (LEMMS) and (d) the composition measurement system (CMS). The various detectors are labeled by letters of the alphabet. MCP = multichannel-plate detectors.

The members of the EPD Science Team are listed in Table A, and the general characteristics of the EPD are outlined as follows:

- Mass: 10.5 kg
- Power: 6-W electronics, 4-W heaters
- Size: $19.5 \times 27.0 \times 36.1$ cm
- Two bidirectional telescopes mounted on stepper platform
- 4π steradian coverage
- Geometric factors: ranges from 6×10^{-3} to 5×10^{-1} cm^2·ster, dependent on detector head
- Time resolution: 0.33–2.67 s, record mode; 2–12 m, real-time mode
- Magnetic deflection, energy-loss and energy measurement, and time-of-flight systems
- Energy coverage (MeV/nucleon):

0.020–55	$Z \geq 1$
0.025–16	helium
0.012–11	oxygen
0.010–13	sulfur
0.010–15	iron
0.015–>11	electrons

Table A. Members of the EPD Science Team.

Principal Investigator	D. J. Williams	APL
Co-Investigators	T. P. Armstrong	University of Kansas
	T. A. Fritz	Boston University
	S. M. Krimigis	APL
	L. J. Lanzerotti	Lucent Technologies
	R. W. McEntire	APL
	J. G. Roederer	University of Alaska
	E. C. Roelof	APL
	W. Stüdemann[a]	MPAe
	B. Wilken	MPAe
Theoretical Consultants	W. I. Axford	MPAe
	A. Hasegawa	Osaka University
	L. R. Lyons	Aerospace Corporation
	R. M. Thorne	University of California, Los Angeles

Note: MPAe denotes Max Planck Institute for Aeronomy.
[a]Deceased (7 Dec 1987).

Figure 1. Jupiter, the target of the Galileo mission, shown with Earth for a relative size comparison. The banded atmospheric structure, the great red spot, and other turbulent features stand out clearly.

consists of nearly 90% hydrogen, 10% helium, and traces of methane, ammonia, water, and other material. It has a mass 318 times that of Earth, a radius some 11 times that of Earth (nearly 72,000 km), and a volume approximately 1400 times that of Earth. Its size is sufficient to hold all the planets of the solar system with plenty of room to spare. Despite this size, its rotation time is 9.92 h, giving it the highest co-rotational velocity at its surface of any solar system body, some 45,600 km/h. It possesses a powerful magnetic field (10,000 times that of Earth), defining the strongest and largest magnetosphere (that region of space around a planet dominated by its magnetic field) in the solar system. In fact, the Jovian magnetosphere is the solar system's largest physical object, and if it could be seen from Earth, it would appear larger than the full Moon. Within this magnetosphere there is a mini–solar system of satellites moving in Jupiter's gravitational field—the

large Galilean satellites (Io, Europa, Ganymede, and Callisto, ranging in size from our Moon to the planet Mercury) and at least 12 smaller orbiting bodies. These characteristics make Jupiter an invaluable object of study for insights into solar system formation, planetary formation, atmospheric behavior, magnetospheric behavior, and possibly stellar formation.

Our knowledge of Jupiter and its environment expanded in a spectacular fashion with each set of flyby observations from the Pioneer (December 1973, December 1974), Voyager (March 1979, July 1979), and Ulysses (February 1992) spacecraft. These observations opened up a Jovian world that was not suspected—the surrealistic patterns in Jupiter's atmosphere; the volcanic, icy, and battered Galilean moons; and Jupiter's enormous and magnificent magnetosphere. Galileo will add to these findings by providing the measurements that such flyby missions cannot—detailed and up-close measurements of Jupiter's atmosphere, magnetosphere, and satellites (Fig. 2), and the variation of these measurements with time.

The mission has begun pursuing its objectives by placing a probe into the Jovian atmosphere and inserting the Galileo spacecraft into orbit around Jupiter. The probe has provided the first *in situ* data from Jupiter's atmosphere, and the orbiter will provide the first extended-time histories of atmospheric and magnetospheric variations and several very close flybys of the Galilean satellites Europa, Ganymede, and Callisto.

Figure 3a is a schematic of the Galileo spacecraft, which supports 12 scientific instruments. The total mass of 2550 kg for the configuration as shown includes 925 kg for propellant and 339 kg for the probe. The two radioisotopic thermoelectric generators provided 570 W of power at launch, as well as 485 W at Jupiter arrival more than 6 years later.

The spacecraft has a dual-spin configuration, where the entire portion above the despun section spins with a nominal rate of 3 rpm. This configuration allows the magnetospheric instruments to obtain their required angular coverage while simultaneously permitting the instruments on the despun section to look in fixed directions for extended periods. A system of slip rings and rotary transformers provides power to and receives signals from the instruments on the despun section. The spin axis is oriented to point toward Earth to provide communications using the 4.8-m-dia. antenna. The long boom supports two scientific instruments at its tip and several others at its base; it measures 10.9 m from the spacecraft centerline to its tip. Figure 3b is a picture of the flight spacecraft configuration at Kennedy Space Center just before launch.

(a)

(b)

(c)
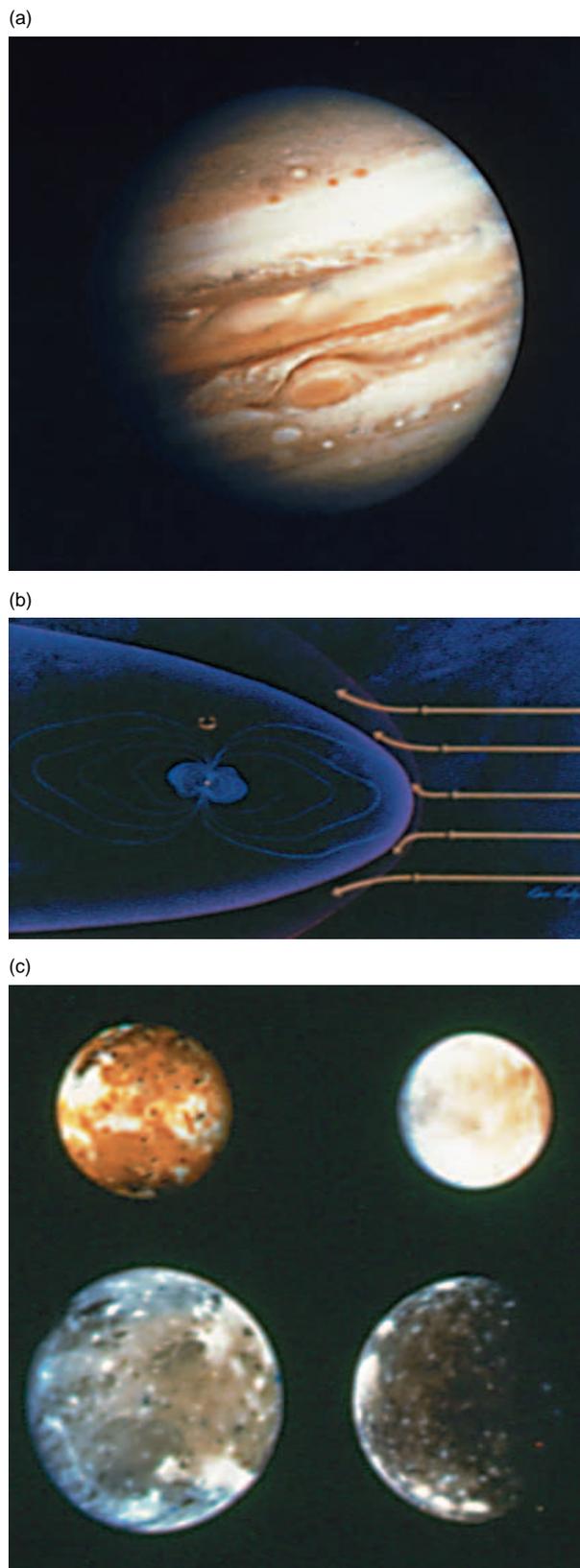
Figure 2. Galileo's three main areas of scientific investigation at Jupiter are (a) the atmosphere, (b) the magnetosphere, and (c) the Galilean satellites. Galileo's imagery will be factors of 100 improved over that of the Voyager spacecraft.

(a)

(b)
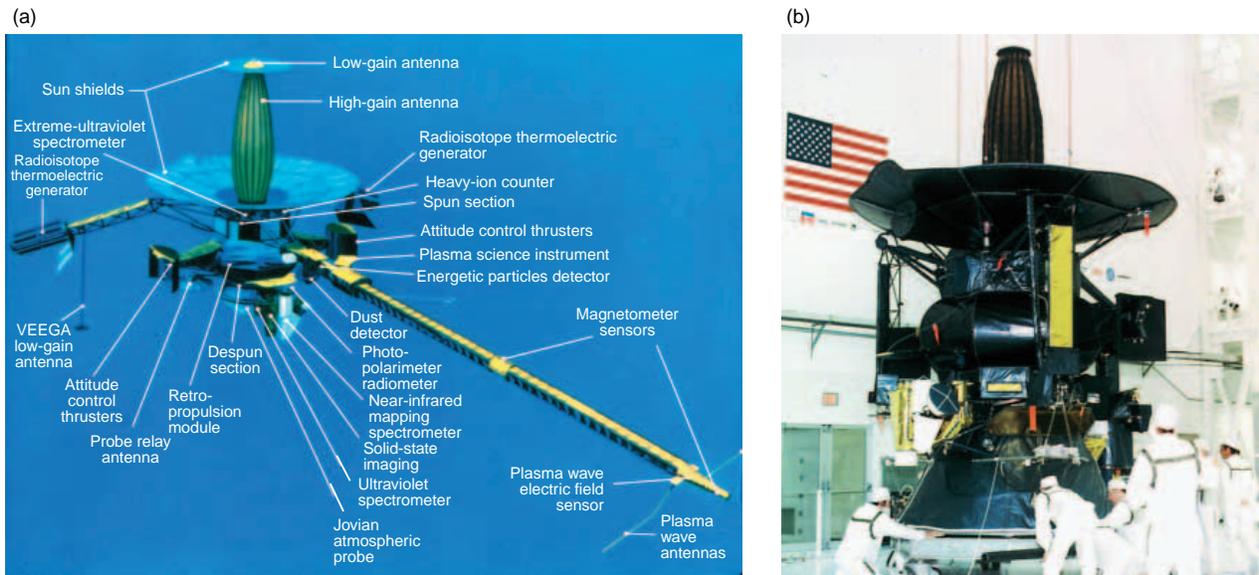
Figure 3. The Galileo spacecraft. (a) A schematic of the Galileo spacecraft in-flight configuration before the (unsuccessful) deployment of the high-gain antenna. Instruments, subsystems, and the probe are indicated; the Energetic Particles Detector is the APL/Max Planck Institute science instrument. (b) The Galileo spacecraft at Kennedy Space Center just before mating with the inertial upper stage booster rocket. Three spacecraft booms have been folded to fit in the shuttle bay.

Figure 4a is a schematic of the atmospheric probe that is pictured in Fig. 4b. The probe descent module supports 7 scientific instruments and was protected by the deceleration module through the fiery plunge into Jupiter's atmosphere. After slowing down to a safe velocity, the deceleration covers were ejected, and the probe parachuted slowly through the Jovian atmosphere as the prime probe data were collected and transmitted to the orbiter as it passed overhead at an altitude of nearly 215,000 km.

The Galileo project is managed by the Jet Propulsion Laboratory, which also built the Galileo spacecraft. The 12 scientific instruments carried by the Galileo spacecraft are listed in Table 1. The Galileo probe was managed by NASA's Ames Research Center and was built by Hughes Space and Communications Company. Lockheed Martin Hypersonic Systems supplied the probe's heat shield. The 7 scientific instruments carried by the probe are listed in Table 2.

(a)

(b)
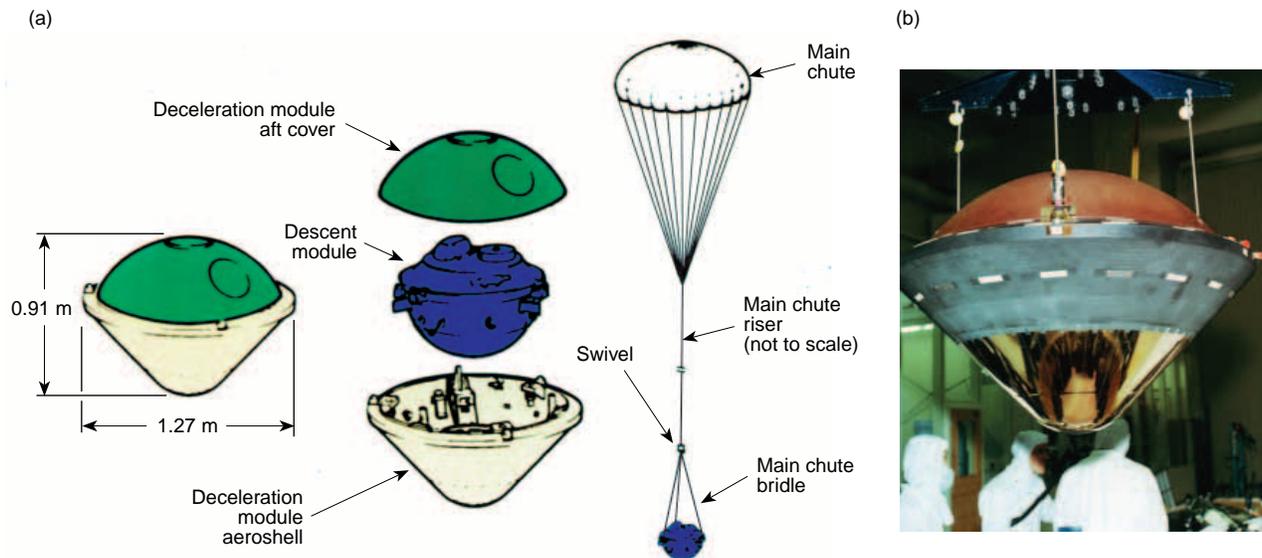
Figure 4. The Galileo probe. (a) A schematic of the probe showing the major components that protect it during its fiery entry into the Jovian atmosphere and then gently lower it into the depths of that atmosphere. (b) The assembled Galileo probe as configured during descent.

Table 1. Scientific instruments carried by the Galileo spacecraft.

Instrument	Principal Investigator/Team Leader	Objectives
Remote sensing (despun)		
SSI	Michael Belton, National Optical Astronomy Observatories	Galilean satellites, high resolution, atmospheric small-scale dynamics
NIMS	Robert Carlson, Jet Propulsion Laboratory	Surface/atmospheric composition thermal mapping
PPR	James Hansen, Goddard Institute for Space Studies	Atmospheric particles, thermal/reflected radiation
UVS/EUV	Charles Hord, University of Colorado	Atmospheric gases, aerosols, etc.
Fields and particles (spinning)		
MAG	Margaret Kivelson, University of California, Los Angeles	Strength and fluctuations of magnetic fields
EPD	Donald Williams, The Johns Hopkins University Applied Physics Laboratory	Electrons, protons, heavy ions
PLS	Lou Frank, University of Iowa	Composition, energy, distribution of ions
PWS	Donald Gurnett, University of Iowa	Electromagnetic waves and wave particle interactions
DDS	Eberhard Grün, Max Planck Institut für Kernphysik	Mass, velocity, charge of sub-micrometer particles
Engineering experiment		
HIC	Edward Stone, California Institute of Technology	Spacecraft charged-particle environment
Radio science		
Celestial mechanics	John Anderson, Jet Propulsion Laboratory	Masses and internal structures of bodies from s/c tracking
Propagation	H. Taylor Howard, Stanford University	Satellite radii and atmospheric structure from radio propagation

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THE JOURNEY TO JUPITER

The launch of Galileo occurred on 18 October 1989, the fifth and last of a series of launch dates established for the program. Originally scheduled for launch in January 1982, program delays resulted in a final and firm launch date of May 1986. Had that launch date held, Galileo would have followed a direct path to Jupiter, taking 31 months to reach its destination,

Table 2. Scientific instruments carried by the Galileo probe.

Experiment	Principal Investigator/Institution	Objectives
Atmospheric structure	Alvin Seiff, San Jose State University Foundation	Temperature, pressure, density, molecular weight profiles
Neutral mass spectrometer	Hasso Niemann, NASA Goddard	Chemical composition
Helium abundance	Ulf von Zahn, Institut für Atmospharenphysik an der Universität Rostock	Helium/hydrogen ratio
Nephelometer	Boris Ragent, San Jose State University Foundation	Clouds, solid/liquid particles
Net flux radiometer	Larry Sromovsky, University of Wisconsin	Thermal/solar energy profiles
Lightning and radio emissions/energetic particles	Louis Lanzerotti, Bell Laboratories, and Klaus Rinnert, Max Planck Institut für Aeronomie Harald Fischer Institut für Reine and Angewandte Kernphysik, Universität Kiel	Detect lightning, measure energetic particles
Doppler wind experiment	Dave Atkinson, University of Idaho	Measure winds, learn their energy source

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arriving in December 1988. Tragically, the *Challenger* disaster occurred two launches before the Galileo scheduled liftoff and effectively shut down the nation's civilian launch capability for an extended period. Following the *Challenger* accident, the liquid-fueled booster built to propel Galileo to Jupiter was deemed to be too dangerous to carry in the shuttle bay and, although waiting for launch at the Kennedy Space Center, was declared unusable in the shuttle. At this point, there was no known way to send the Galileo spacecraft to Jupiter—the United States did not have the thrust capability for the job, and no other launch vehicle on Earth could do it. (Rumors had the spacecraft being sent to the National Air and Space Museum!)

A remarkable solution was then discovered. It entailed using the maximum available U.S. launch capability to get the Galileo spacecraft to Venus. Although this plan would send Galileo in the wrong direction (toward the Sun rather than away), it al-

lowed the trajectory experts at the Jet Propulsion Laboratory to use planetary gravitational assists to design Galileo's flight path. Thus, they began to devise a way of getting Galileo to Jupiter. This game of planetary ricochet resulted in the Venus–Earth–Earth-Gravitational-Assist (VEEGA) trajectory shown in Fig. 5. It contains one gravitational assist flyby of Venus (10 February 1990), two of Earth (8 December 1990 and 8 December 1992), and numerous scientific targets of opportunity. The altitudes of these flybys were 14,400 km at Venus, 944 km at Earth-1, and 304 km at Earth-2. The power of such planetary flybys in developing interplanetary trajectories is illustrated by the fact that the Earth-1 flyby provided an energy boost roughly equivalent to that obtained at launch. The price paid for this seemingly low-cost method of obtaining extra launch capability is that the path flown (Fig. 5) took nearly 74 months, compared with 31 months for the direct flight.
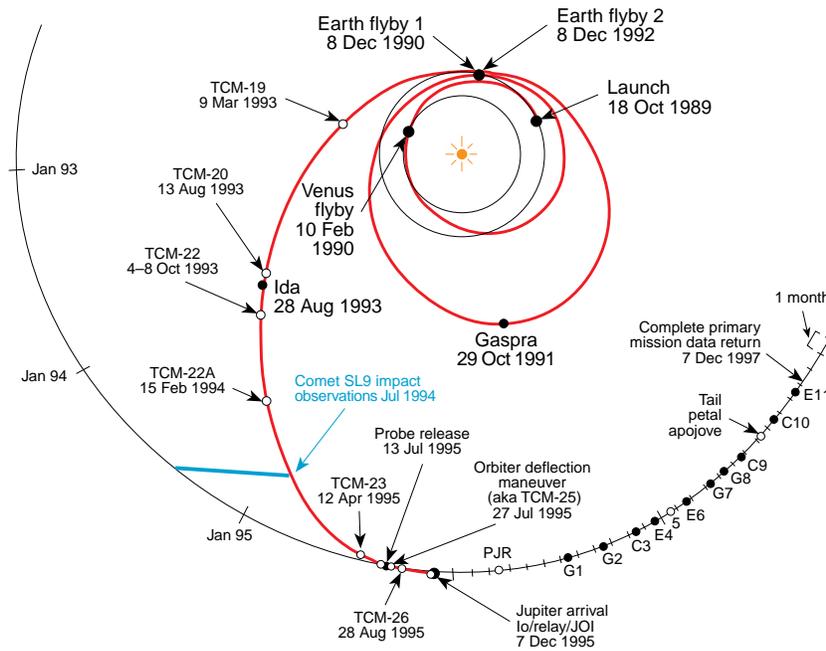
Figure 5. The Galileo Venus–Earth–Earth-Gravitational-Assist (VEEGA) trajectory to Jupiter. Events and encounters on this more than 6-year journey are indicated in the figure. The satellite encounters are indicated as follows: G = Ganymede, C = Callisto, E = Europa. Galileo has completed the G1 and G2 encounters, and the C3 encounter takes place on 4 November 1996. TCM = trajectory control maneuver, PJR = perijove raise maneuver.

For Galileo, this new flight strategy raised another concern, namely, the reliability of the spacecraft and its instrumentation. To meet the original final launch date of May 1986 (the flight spacecraft was at Cape Canaveral being prepared for launch at the time of the *Challenger* accident), flight parts and systems were tested and assembled in 1984–85. For a May 1986 launch and a December 1988 arrival, the flight spacecraft would have been 4 to 5 years old. However, for the new scenario with launch in October 1989 and arrival in December 1995, the Galileo spacecraft would be (and now is) 11 to 12 years old when it began its planned mission. Would it last? To date, the answer is a resounding yes—with the exception of one very important component, the high-gain antenna (HGA).

A CHANGE OF PLANS

When unfurled, the 4.8-m HGA should appear as shown in Fig. 6a. The small circular structure at the top of the HGA mast is one of several sunshades that were added to protect Galileo subsystems from the increased solar heat at Venus. Were it not folded and shielded from the Sun by this shade, the HGA would have suffered severe thermal damage to the delicate wire mesh that formed its parabolic dish. On 11 April 1991, when heat from the Sun no longer posed a thermal problem, commands were sent to unfurl the HGA. The commands were received; however, the drive motors stalled and the HGA did not open. A detailed analysis of motor current, spin rate, and Sun sensor data showed that most likely three ribs of the HGA were stuck and did not deploy and that the actual HGA configuration was as shown in Fig. 6b. Calculations, simulations, and laboratory tests of spare HGA systems led to a series of corrective procedures that have been employed throughout the flight of Galileo. None have worked, and the HGA remains only partially unfurled and useless.

This failure caused the Galileo project team to rework the entire mission plan based on the low-gain antenna (LGA). In terms of science data rate, the impact is enormous; the average data rate for the LGA mission is 50 to 60 bits per second (bps), compared with the HGA capability of 134,000 bps—a reduction of a factor of 2000! However, as we shall see, the impact on scientific return is comparatively minimal as 70% of the scientific objectives are still being met.

The reasons for this minimal impact are the flexibility and adaptability of the Galileo spacecraft and the ingenuity of the project and science teams in reworking the mission. All probe data objectives were met; its data were transmitted to the orbiter, stored on the tape recorder, and rebroadcast to Earth as originally planned except that the time required to transmit the data to Earth was much longer because of the lower data rate. By extensively reprogramming the spacecraft and all instrument data systems after successful receipt of probe data, by using the tape recorder as a storage buffer from which data could be selected, and by incorporating new data compression techniques, the Galileo orbiter will return thousands of remote sensing observations of the Jovian atmosphere and the Galilean satellites and will provide a nearly continuous measure of the magnetospheric environment throughout the mission orbital tour.

The change in plans has worked amazingly well so far. Probe release on a precise Jupiter-impact trajectory, main engine firing, probe arrival, orbiter positioning and orientation, orbit insertion, transmission of probe data to Earth, raising the low point of the first Jupiter orbit (perijove raise), and the beginning of the orbiter science mission have all been executed successfully. Some of these complex activities that are vital to mission success are described in the following sections.

(a)
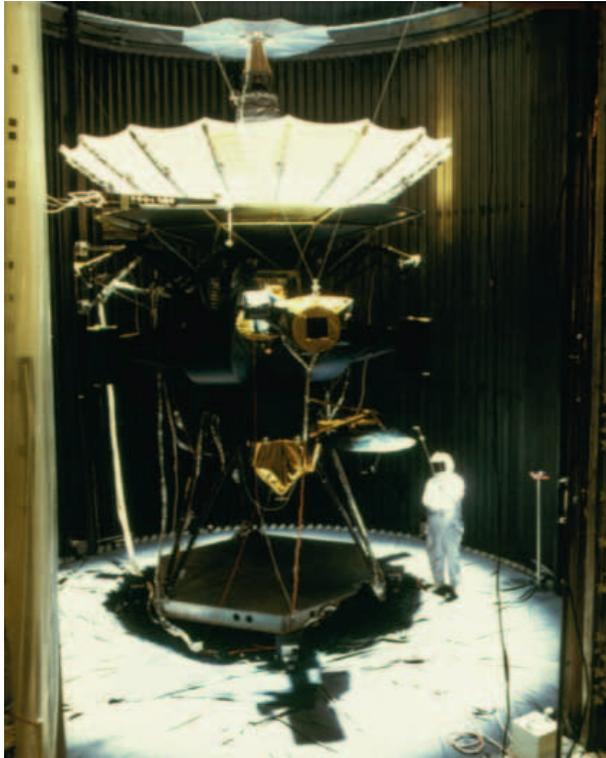
(b)

Figure 6. Galileo's main antenna. (a) The Galileo spacecraft in an environmental chamber with its high-gain antenna unfurled. (b) The most likely configuration of the high-gain antenna following its unsuccessful deployment in April 1991. The analysis of data from the spacecraft and laboratory tests using a spare antenna showed that three ribs on the main antenna are stuck, keeping the antenna from deploying.

PROBE RELEASE

Following in-flight electrical tests of the probe in March 1995 (the first in 27 months) and again in July 1995, the probe was released on 13 July 1995, some 430 million mi from Earth and 51 million mi from Jupiter

(see Fig. 5). It was inserted into a passive ballistic trajectory lasting for 147 days and culminating with its entry into the Jovian atmosphere on 7 December 1995. The Galileo spacecraft, after maneuvering into the precise entry trajectory for the probe, oriented its spin axis to align exactly in inertial space with the probe's entry velocity vector. Just before release, the spacecraft spun up to 10.5 rpm to provide the necessary spin stability to the probe for its 5-month flight to Jupiter.

With the probe successfully released and on its extended cruise to Jupiter, the Galileo spacecraft faced another critical point in its mission, namely, the first firing of its main engine for a trajectory adjust maneuver. This adjustment was critical not only to avoid having the Galileo orbiter follow the probe to a fiery death in the Jovian atmosphere, but also to position it to arrive precisely above the probe nearly 5 months later in order to receive the probe data during its descent into the Jovian atmosphere. The 5-min 3-s burn of the main engine on 27 July 1995 was nominal, performing to within 1% of expectations. The Galileo orbiter would be hearing from the probe in approximately 133 days.

ARRIVAL AT JUPITER

On the approach to Jupiter, fate again tested the capability of the Galileo spacecraft and project to overcome major problems and setbacks. A tape recorder anomaly occurred following a rewind command issued just after the Galileo camera had finished taking a series of pictures of Jupiter and its satellites. Once again, the expertise of the project team coupled with the adaptability of the spacecraft led to recovery from this anomaly. However, further restrictions were required for the safe future operation of the mission; the pictures of Jupiter with its satellites, already on the tape, could not be played back, and no additional pictures could be taken during the approach, during the Io encounter, and at the close passage to Jupiter. New and safe tape recorder operations had to be identified and tested by the time of the first satellite encounter of Ganymede on 27 June 1996. Although the lack of approach images and the loss of images during the close encounter of Io were major disappointments (moderate-resolution images of Io will still be obtained), during its nominal lifetime of 2 years, Galileo will provide superb images of Jupiter and the satellites Europa, Ganymede, and Callisto at resolutions hundreds of times improved over previous pictures.

Despite these traumatic events, both the Galileo spacecraft and the probe continued toward their historic rendezvous with Jupiter. Their arrival on 7 December 1995, 147 days after the probe release, is depicted in Fig. 7. A timer set by the orbiter at the probe release turned on the probe well outside the orbit of Io,
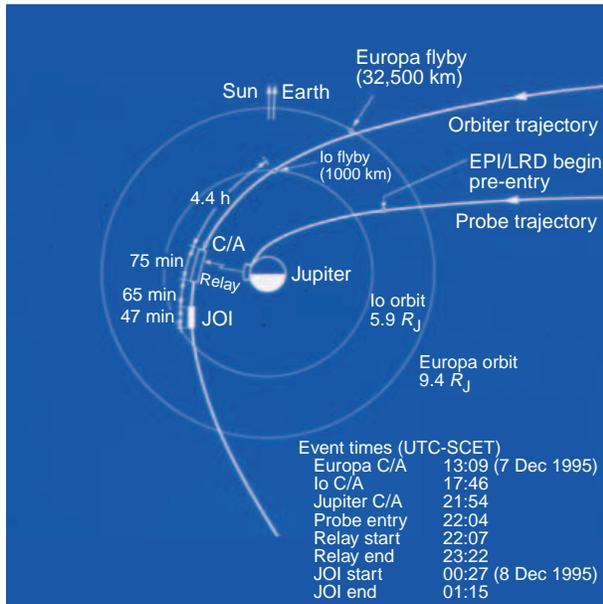
Figure 7. Diagram of the probe and Galileo spacecraft arrival geometry on 7 December 1995, 147 days after release of the probe. The Io flyby occurred at an altitude of 898 km followed by successful receipt of nearly 58 min of probe data during the relay interval shown in the figure. This event was followed by the main engine Jupiter orbit insertion burn that placed the Galileo spacecraft into orbit around Jupiter. EPI/LRD = energetic particle instrument/lightning and radio emissions detector, C/A = closest approach, JOI = Jupiter orbit insertion, R_J = radius of Jupiter (71,492 km), UTC = Coordinated Universal Time, SCET = spacecraft event time.

as indicated in Fig. 7. Several measurements of radiation belt particles were made as the probe dropped toward the atmosphere. The prime atmospheric measurements were made during the "relay" interval in Fig. 7. As the Galileo spacecraft approached its rendezvous point for reception of the probe's signals, it first recorded data from the particles and fields instruments during the encounter with Io. After recording data through the Io torus (a doughnut-shaped region of gas around Jupiter formed by the volcanoes of Io) and at closest approach (900 km), the spacecraft pointed its probe relay antenna toward the expected position of the probe and waited for the probe data to arrive. More than 6 years of hard work and mounting anxieties came to a glorious climax when Galileo transmissions arrived at Earth (52 min after the fact because of the one-way light travel time at that distance), signaling the successful receipt of probe data at the spacecraft. The Galileo project had completed the first-ever penetration of the Jovian atmosphere by a scientific probe.

Figure 8 shows a diagram of this spectacular and successful probe descent. Because of Jupiter's tremendous gravitational pull, the probe approached Jupiter's atmosphere at a speed of nearly 171,000 km/h. During the first 2 min of its descent, the probe heat shield experienced temperatures twice as high as the Sun's surface and deceleration forces of 230 g's while being slowed down by this exotic atmosphere. The precision of the probe trajectory set by the Galileo spacecraft 147 days earlier was such that its entry flight-path angle could not vary by more than 1.6° of nominal; otherwise, the probe would have either glanced off the atmosphere or would have been destroyed by aerodynamic forces due to a steeper entry angle.

Having spent well over half of its mass protecting the probe, the forward heat shield was released when the probe reached a speed of 3000 km/h. Then, with the probe's parachutes deployed, the radio link to the Galileo spacecraft was established and data transmission began. Transmission lasted for 57.6 min, terminating at an atmospheric depth of 23 bar (1 bar is the surface atmospheric pressure at Earth) and a temperature above 150°C. The ultimate fate of the probe was to be vaporized by the extreme temperatures deep within Jupiter's interior and thus itself become a part of Jupiter's atmosphere.

POST-ARRIVAL

Shortly after Galileo received and stored the probe data, another critical maneuver had to be executed, namely, a long burn of the main engine that would insert Galileo into orbit about Jupiter. The 49-min firing went as scheduled, and the Galileo spacecraft officially became the Galileo orbiter, the first artificial object ever to join Jupiter's family of satellites.

Most of the time of the nearly 7-month-long initial orbit (Fig. 9) has been taken up with transmitting the probe data, testing the tape recorder for the new mission mode requirements, loading and testing the new software, transmitting the data taken at the Io encounter, and preparing for the first encounter with Ganymede on 27 June 1996. Near apojove (the orbit's high point above Jupiter) on 14 March 1996, the main engine was fired for the third and last time to raise the altitude of the orbit's low point (perijove) out of Jupiter's intense radiation belt (nearly one-half of Galileo's total 2-year radiation dose comes from the initial low-altitude pass at Jupiter encounter).

Using the same gravitational assist technique that propelled Galileo to Jupiter, the orbiter will now use the Galilean satellites of Jupiter to accomplish the orbital tour of Jupiter shown in Fig. 9. This tour provides 10 close encounters with the satellites Europa, Ganymede, and Callisto; the closest approaches will be as low as 300 km, many hundreds of times closer than previous flybys. To illustrate the enormous difference in encounter altitudes, we refer to Fig. 10, an image of Europa taken by Voyager 2 cameras at a
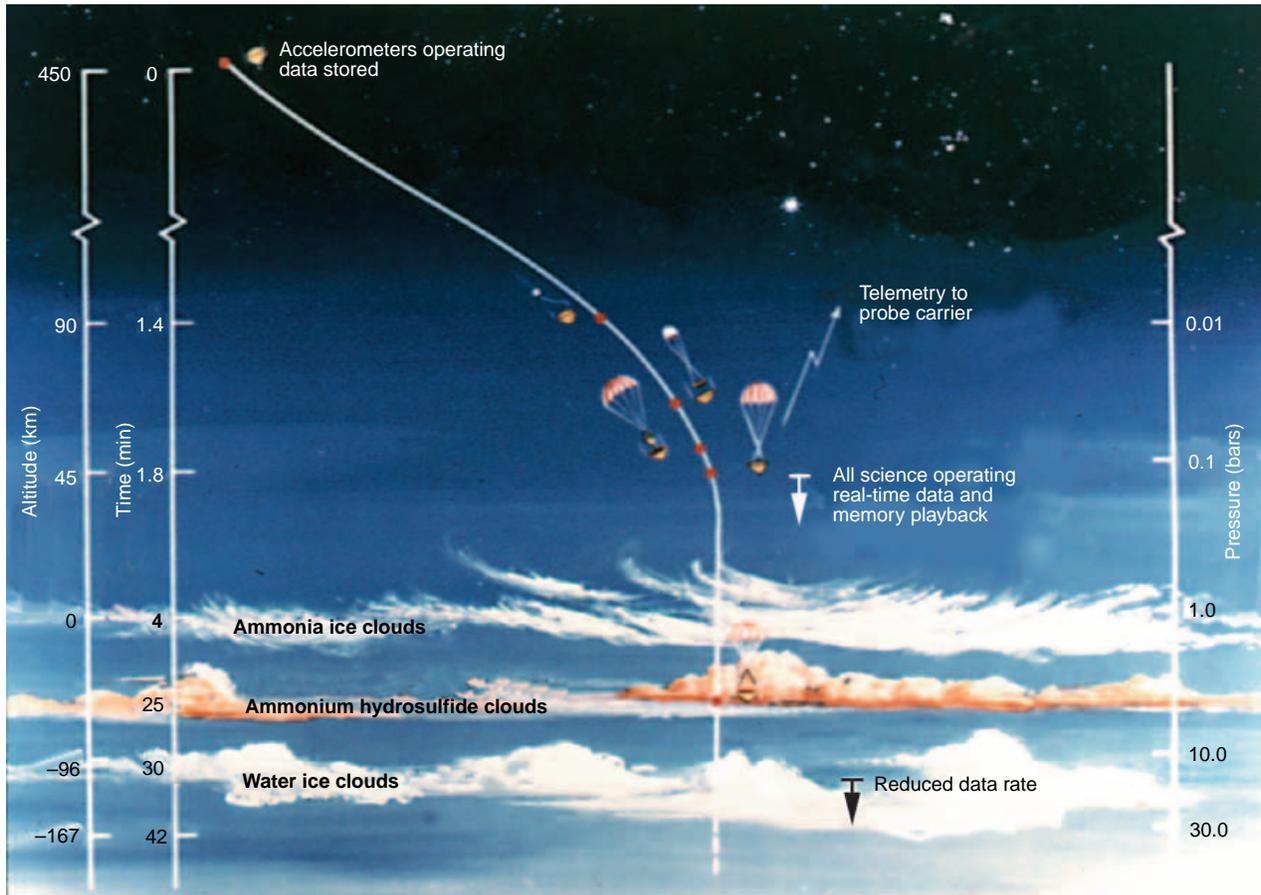
Figure 8. Diagram illustrating probe entry and descent into the Jovian atmosphere. After experiencing deceleration forces of up to 230 *g*'s and heat shield temperatures twice as high as the surface of the Sun, the protective heat shield was released and the probe gently descended via parachute into the Jovian atmosphere. Data were retrieved continuously from the probe down to an atmospheric depth of 24 bar, roughly 160 km below the top layer of clouds.

G1	27 Jun 96
G2	6 Sep 96
C3	4 Nov 96
E4	19 Dec 96
E6	20 Feb 97
G7	5 Apr 97
G8	7 May 97
C9	25 Jun 97
C10	17 Sep 97
E11	6 Nov 97
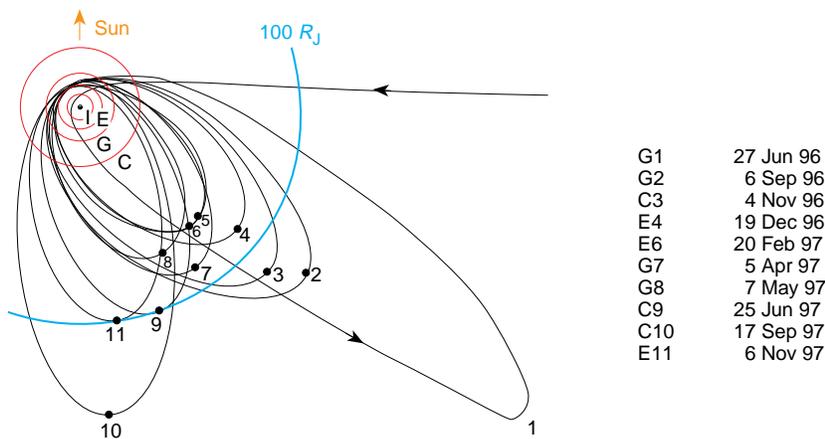
Figure 9. Orbital tour of the Jovian environment. Orbit 1 resulted from the main engine burn just after receipt of the probe data plus a perijove raise burn that occurred at apojove. Orbits 2 through 11 resulted from planned gravity assist flybys of the Galilean satellites that yielded both close satellite encounters and orbits providing the exploration of completely new regions of the Jovian system. I = Io, E = Europa, G = Ganymede, C = Callisto, and R_J = radius of Jupiter (71,492 km).

distance of approximately 240,000 km. Europa, a smooth, billiard ball–like moon, is thought to have a shifting icy surface some 100 km thick. The lines on the surface are thought to be cracks and measure up to several thousand kilometers long and up to 200 to 300 km wide. The Galileo orbiter will fly over the surface of Europa at a distance equivalent to the width of the cracks shown in Fig. 10. By comparing the Galileo flyby distance to the nominal Voyager distance of greater than 80,000 km, it is clear that the improvement in resolution will be huge (many factors of 100) and will reveal sights yet unimaginable.
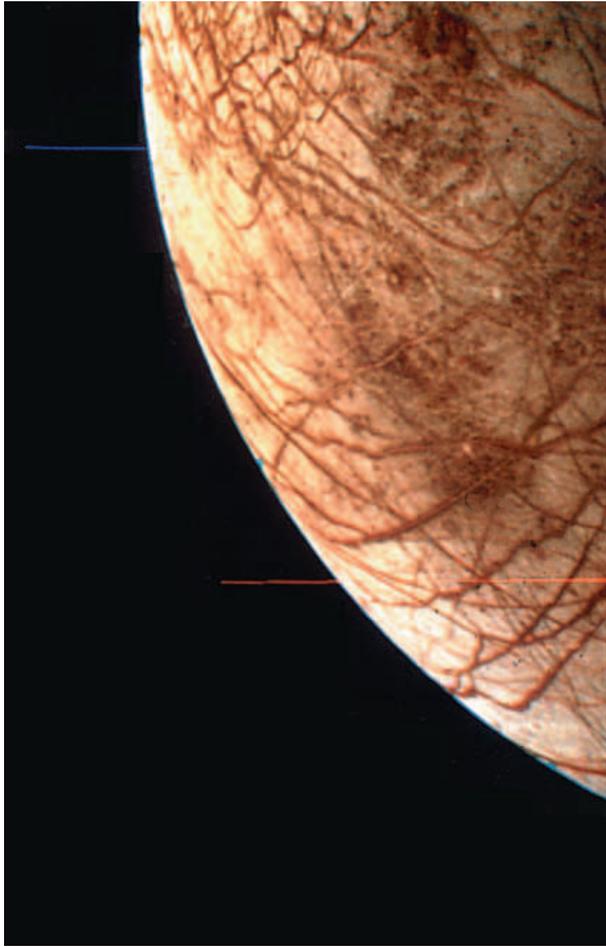
Figure 10. The nature of Galileo's close encounters with the major Jovian moons is illustrated by this picture of Europa, taken by Voyager 2 cameras at a distance of 240,000 km. The cracks seen on Europa's icy surface are up to several thousand km long and 300 km wide. The Galileo orbiter will fly by Europa at a distance equivalent to the width of the cracks seen in the figure.

SIGHTS ALONG THE WAY

The instruments onboard Galileo have recorded many wondrous sights and new discoveries during the more than 6-year journey to Jupiter. In the following sections, we present a sampling of these observations to demonstrate the flexibility of the spacecraft in accommodating unplanned and serendipitous measurements, to highlight the capability of the instruments, and to illustrate data quality at the low information rates of the new mission profile. Of the numerous observations made at these interplanetary encounters, we shall present only one or two from each because of space limitations. In all of the examples discussed, the spacecraft operated on its own without real-time guidance from its Earth-based controllers. Using instruction sequences provided beforehand, the spacecraft autonomously performed the required maneuvers, turned on the instruments, set the measurement modes, recorded

the observations, and at the end of the observation session returned the instruments and other spacecraft systems to their normal interplanetary cruise mode. The outstanding successes achieved to date demonstrate how superb an interplanetary laboratory the Galileo spacecraft is and how well designed and understood it is by its Earth-bound project team.

Venus

Less than 4 months after launch, the Galileo spacecraft encountered Venus on 10 February 1990 for the first of its three gravitational assists to Jupiter. Using instruction sequences provided earlier in the flight, Galileo obtained a variety of measurements pertaining to Venus' atmosphere and environment. These data were recorded on the tape recorder, and because of the low available data rates (remember that the main antenna remained stowed behind a sunshade for protection), they were not transmitted to Earth until available data rates allowed them to be in November 1990, some 9 months later.

Initial results from the Galileo encounter with Venus appeared in Ref. 4. Among the measurements reported were those from the APL instrument, the EPD. These observations, shown in Fig. 11, provided the first-ever detection of energetic particles associated with the bow shock of Venus, a standing shock produced by the impact of the supersonic solar wind with the ionosphere and atmosphere of Venus. The fact that Venus' bow shock can accelerate ions to hundreds of kiloelectronvolts in energy came as a surprise. The bow shock geometry, the distance of Galileo from the shock, and the gyroradii of the particles observed place stringent limits on contending theories of the acceleration of interplanetary particles.

Earth-1

Galileo encountered Earth on 8 December 1990 for the second of its three gravitational assists. The closest-approach altitude for this encounter was 960 km, and it added 18,600 km/h to Galileo's speed relative to the Sun. This gravitational assist also redirected Galileo's trajectory to encounter the asteroid Gaspra in October 1991 and Earth in December 1992. During the several days before and after the encounter, the spacecraft gathered much data about our planet, our Moon, and our magnetosphere. These data provided new insights of Earth's environment, a view of Earth from the perspective of an interplanetary explorer, and in-flight calibrations of the instruments in a known environment that complemented and extended ground calibrations.

Figure 12 is a color image of Earth taken on 11 December 1990 when the spacecraft was about 2.1 million km from Earth. South America is in the center of the image, and the white sunlit continent of

(a)

Ions
log E
(keV)

h:min	05:40	06:00	06:20	06:40
VSE x (R_v)	−0.3	1.1	2.4	6.9
y	3.3	2.6	1.7	−1.9
z	−2.0	−2.4	−2.6	−3.0

log J

(b)

Counts per second

120–280 keV

65–120 keV

42–65 keV

22–42 keV

05:40   06:00   06:20   06:40

10 Feb 1990, Day 41

(c)

Bow shock

Data gap

0700

Galileo
spin axis

0500

0300 UT

y (R_v)

x (R_v)
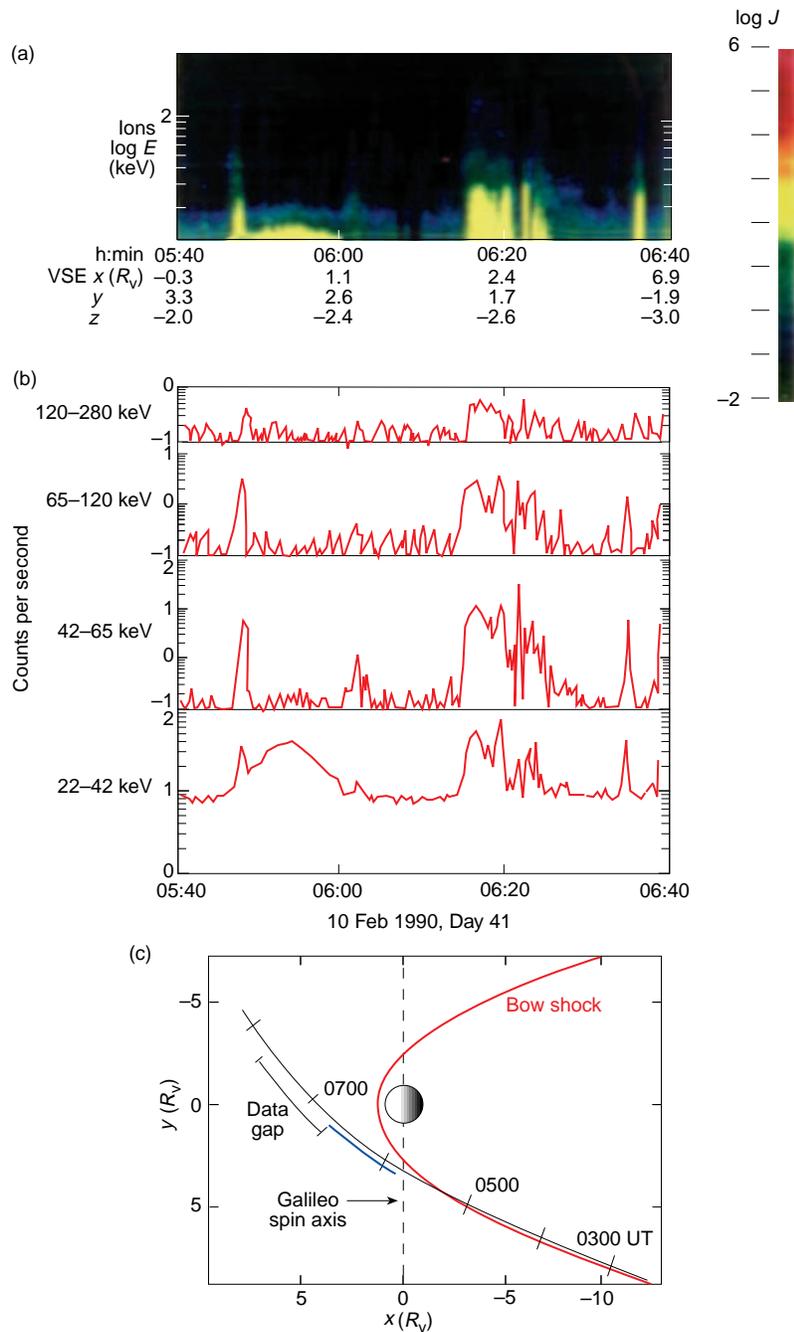
Figure 11. Energetic Particles Detector measurements at Venus. (a) Energy (E) is plotted vs. time. The observed fluxes (J) are color coded according to the bar on the right. (b) Individual channel count rates. All particles arrived at the spacecraft from the direction of Venus. (c) Galileo's trajectory by Venus. The blue bar indicates where the EPD measured energetic ions coming from Venus. VSE = Venus solar ecliptic, R_V = Venus radii.

about 3.8 billion years ago by the impact of an asteroid-size body. The part of the Moon seen at Earth is on the right, and the lunar far side is on the left. The Aitken Basin, larger (1900 km in diameter) and older than the Oriental Basin, can be seen in the lower left of Fig. 13.

Galileo's flyby of Earth represents the first planetary-type encounter of our planet with a satellite. In fact, arriving here after passing by Venus makes Galileo the first confirmed interplanetary visitor to Earth. Comparing what is known about Earth with the interpretations of what was measured during this flyby provided Galileo scientists with a valuable evaluation of their planetary flyby interpretation methods. The measurements verified Earth's mass, diameter, composition, magnetic field, aurorae, magnetosphere, and atmospheric composition. In a different vein, Galileo's detection of oxygen, carbon dioxide, methane, nitrous oxide, and their relative abundances, along with unusual radio signals, strongly indicated the presence of biological life on Earth. However, these observations did leave open the question of intelligent life.

Gaspra

Continuing its journey, Galileo was now on a course toward the first close spacecraft encounter with an asteroid, the asteroid 951 Gaspra. Figure 14 shows the highest-resolution picture obtained of this historic encounter. The picture is a mosaic of two images taken by Galileo on 29 October 1991 at a range of 5300 km, approximately 10 min before closest approach. Gaspra is an irregular body with dimensions of about 19 × 12 × 11 km and rotates counterclockwise every 7 h around the north pole, which is located in the upper left of the figure. The abundance of small craters is a striking feature of Gaspra's surface. More than 600 craters from 100 to 500 m in diameter are visible in the figure. Although the plasma instrument and EPD

Antarctica is below. This figure is the first frame of a spectacular 1400-frame time-lapse motion picture showing Earth spinning in space.

Figure 13 is an image of the western hemisphere of the Moon taken on 9 December 1990 at a range of 560,000 km. The Oriental Basin is in the center of the image. It is about 1000 km in diameter and was formed

Figure 12. Image of Earth taken by Galileo on 11 December 1990.
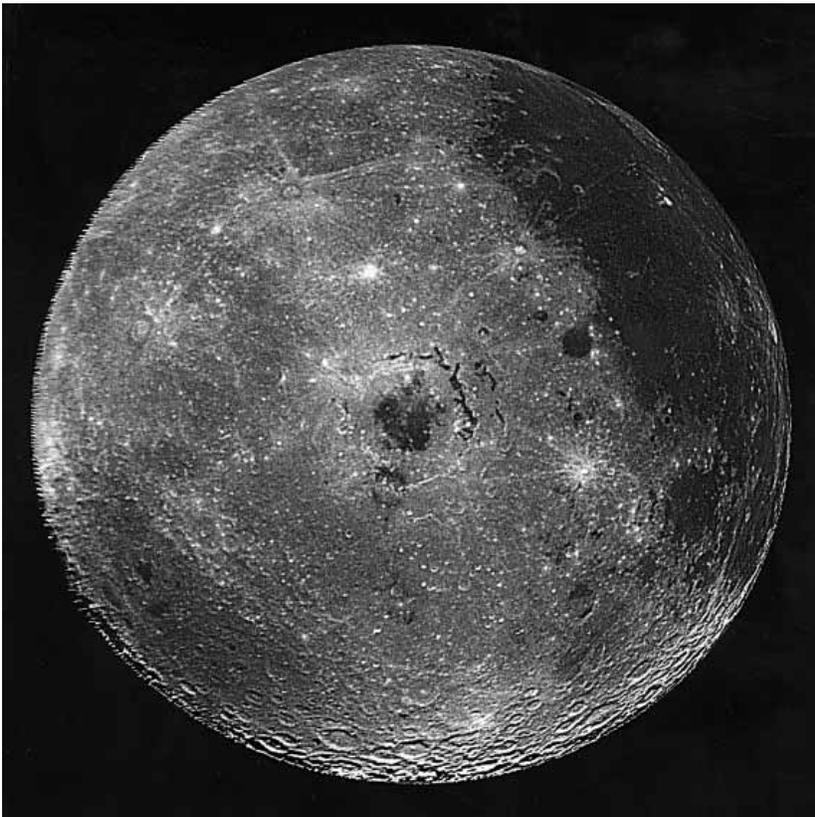
Figure 13. A Galileo image of the western hemisphere of the Moon taken on 9 December 1990.

detected no effects that could be attributed to Gaspra, the magnetometer observed perturbations that possibly were linked to the asteroid, thereby providing an upper limit to the intrinsic magnetic field of that body.

Most of the Gaspra images were stored on the tape recorder for over a year and then were transmitted to Earth in November 1992 when the data rate increased as the spacecraft again approached Earth. However, to satisfy everyone's curiosity and return early images of the asteroid during this low-data-rate period (<40 bits/s), the project used a technique that would prove very valuable in optimizing the enforced low data rates at Jupiter. Using improved navigation accuracies, the project team determined which image frames and which scan lines within those frames contained the asteroid and subsequently transmitted only that portion of the image data. This technique worked beautifully; early images of Gaspra were available on the ground for analysis, and scientists now had a method to obtain an expanded set of useful images of Jupiter.

Earth-2

Following the Gaspra rendezvous, Galileo proceeded toward its third and last gravitational assist, the second Earth encounter. This final gravitational boost placed Galileo on a direct course to Jupiter with a close passage of the asteroid 243 Ida. On approach to Earth, images of Gaspra stored on the tape recorder for the past year were transmitted to Earth, and a second set of detailed Earth observations was gathered by the Galileo instruments. These data, together with data from the Earth-1 passage, have provided a unique and valuable archive of Earth environment data that continue to be studied. On 16 December 1992, its long farewell ending, Galileo sent Earth a

Figure 14. Highest resolution picture of asteroid 951 Gaspra, taken by Galileo during the first close encounter of a spacecraft with an asteroid.

Ref. 5. Because the impact site was on the far side of Jupiter, the telescopes were unable to view it directly. Galileo, however, was in a position to view the impact site directly and contributed significant data on the impact.

On 17 May 1994, the comet SL9 appeared as shown in Fig. 17. This picture was taken by the Hubble Space Telescope wide-field planetary camera. The apparent separation of fragments A and W was about 360 arcsec and corresponds to a projected distance of 1.15 million km. The four images in Fig. 18 show Galileo's perspective of the impact of fragment W with Jupiter's atmosphere on 22 July 1994. The images were taken at intervals of 2.33 s at a range of 238 million km. The first image shows no impact. A point of light appears in the second image, maximizes in the third image to the point of saturating its picture element, and fades away in the fourth image. These

last parting look at its birthplace (Fig. 15) as it began the last leg of its epoch journey to Jupiter.

Ida

Galileo was now headed toward its predestined meeting with Ida before its arrival at Jupiter. The encounter with Ida occurred on 28 August 1993 and provided Galileo with another discovery. Figure 16a shows the first full picture of asteroid 243 Ida and its previously unknown and unexpected companion, a small natural moon. This is the first conclusive evidence that natural satellites of asteroids exist. The portrait, taken at a range of 10,500 km, shows Ida to be a heavily cratered, irregularly shaped object some 56 km long. The satellite, subsequently named Dactyl by the International Astronomical Union, is 1.6 km in diameter and approximately 100 km from the center of Ida. Figure 16b shows a close-up of Dactyl taken at a range of 3900 km. More than a dozen craters greater than 80 m in diameter are visible in this view.

Shoemaker-Levy 9

As if to make up for all the trials and tribulations suffered by Galileo, Mother Nature staged one of the most dramatic events ever witnessed in the solar system—the impact of the Shoemaker–Levy 9 (SL9) comet train with the atmosphere of Jupiter. Earth-based telescopes and the Hubble Space Telescope captured spectacular pictures of the aftermath of the impact. Analyses of these pictures were published in

Figure 15. Galileo's parting view of the Earth and Moon as it began the final leg of its journey to Jupiter.

Figure 16. (a) Galileo's second encounter with an asteroid shows that asteroid 243 Ida has a moon of its own. (b) A closeup of Ida's newly discovered moon, Dactyl.

END OF JOURNEY, BEGINNING OF MISSION

Galileo arrived at Jupiter on 7 December 1995, having completed its adventurous tour of the inner solar system. Each visit on the tour provided not only an excellent set of pictures, but also new discoveries about these guideposts along the way to Jupiter. In keeping with the long string of new findings, the probe descent into the Jovian atmosphere and the insertion of the Galileo spacecraft into orbit around Jupiter have been unqualified successes. The Galileo mission has begun and to date has exceeded early expectations.

Results from the probe[6] make it necessary to revisit all of our ideas on the formation and evolution of the giant gaseous planets of the outer solar system. The measurements of elemental and molecular abundances, wind velocities, atmospheric temperatures, cloud characteristics, and electrical storms give a much different picture of Jupiter than had been expected.

The ratio of helium to hydrogen by mass was found to be 24%, basically the same as the Sun, implying that the amount of helium in Jupiter's atmosphere remains at the level gathered by Jupiter as it formed from the primordial solar nebula. This finding indicates that the gravitational settling of helium into the depths of Jupiter's atmosphere has proceeded at a much slower pace than on Saturn, where the ratio is about 6%. This difference strongly suggests that Jupiter's interior is much hotter than Saturn's, the next-largest planet in the solar system. It may require a revision of the existing estimates for the size of the rocky core believed to exist at Jupiter's center.

The probe measured winds far stronger than expected throughout its descent into the Jovian atmosphere. The persistence of wind speeds of up to 700 km/h to far below the one cloud layer detected strongly suggests that heat from Jupiter's interior drives the winds, rather than solar heating.

and other remote sensing data from Galileo have been used in combination with Hubble and ground observatory data to help determine certain features of the impact, e.g., they were cometary fragments, they did not penetrate deeply into the Jovian atmosphere, the largest fragment was about 0.5 km in size, and the fragments disturbed not only the atmosphere but also the magnetosphere and radiation belts. Because of this last finding, we plan to search for remnants of cometary material in the Jovian magnetosphere—an improbable but tantalizing possibility.

Figure 17. A picture of the fragmented comet Shoemaker–Levy 9 taken by the Hubble Space Telescope in mid-May 1994 before the impact with Jupiter.

Figure 18. Galileo images of the impact of fragment W of comet Shoemaker–Levy 9 with the Jovian atmosphere. These images, taken 2.33 s apart, are the only direct images of the impact area and have provided important correlative measurements with Earth-based observations.

area found on Earth, although the individual events were roughly 10 times as energetic as those on Earth.

These results indicate that the probe entered a dry, hot spot in the Jovian atmosphere. They are consistent with extensive Earth-based observations of Jupiter and the probe entry site made shortly before probe arrival. They have also provided plentiful material for new insights regarding planetary, solar, and stellar evolution.

Data gathering from the probe has been completed, and data gathering from the orbiter has just begun. The first orbiter data transmitted to Earth were the data recorded during the close passage of Io. Results of the radio science celestial mechanics experiment[7] show that Io has a metallic core (most likely iron and iron sulfide) about 900 km in radius and surrounded by partially molten rock and crust. Early results from the magnetometer experiment[8] show a large (nearly 40%) decrease in Jupiter's magnetic field associated with the Io closest approach. This finding has been interpreted by the magnetometer team as indicative of an intrinsic Ionian magnetic field, consistent with the newly discovered iron core of that moon. If the detailed data transmitted from the tape recorder sustain this interpretation, Io will be only the third solid body in the solar system, in addition to Earth and Mercury, that has an intrinsic magnetic field.

Much less water was measured than expected. From probe measurements, the amount of water in the Jovian atmosphere is about one-fifth of that in the solar atmosphere, based on the Sun's oxygen-to-hydrogen ratio. Earlier observations from the Voyager spacecraft and estimates derived from the atmospheric response to the SL9 impact led to the conclusion that Jupiter's water content was up to 10 times that of the Sun's.

Consistent with the results indicating that Jupiter is a much drier place than previously thought was the observation of only one tenuous cloud layer where three distinct layers were predicted. Probe instruments also detected only one-tenth of the lightning activity per unit

The recorded data provide a cross-sectional measurement through the Io torus, a doughnut-shaped ring of neutral and ionized gas around Jupiter created by the volcanoes of Io (Fig. 19). Galileo's passage by Io at an altitude of 900 km allowed a detailed measure of the interaction of this dynamic satellite with the Jovian magnetosphere and its particle populations. Because Io is a major source of particles for the Jovian magnetosphere, these observations are crucial to understanding the behavior of this protostellar system.

Data from atmospheric observations, satellite encounters, and the orbital tour began to arrive routinely during June–July 1996. The next few years promise to be a time of dramatic and exciting discoveries from Galileo, a solar system wanderer that has finally found its home in the planetary family of Fig. 20.
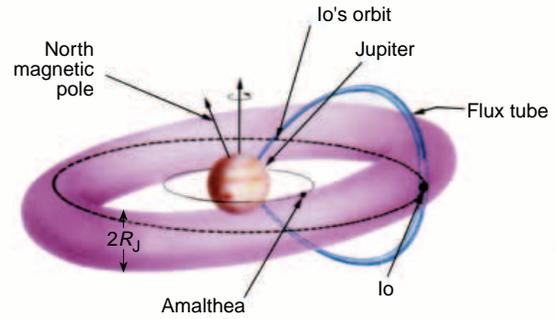
Figure 19. A schematic of the Io torus, a doughnut-shaped ring of neutral and ionized gas around Jupiter created by the volcanoes of Io. On its approach to Jupiter, Galileo flew through the middle of this remarkable structure and obtained data on its characteristics. The data were stored on the tape recorder for later transmission. R_J = radius of Jupiter (71,492 km).

Figure 20. Jupiter and its four Galilean moons—Io, Europa, Callisto, and Ganymede.

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