Galileo Probe: In Situ Observations of Jupiter's Atmosphere

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The Galileo probe performed the first in situ measurements of the atmosphere of Jupiter on 7 December 1995. The probe returned data until it reached a depth corresponding to an atmospheric pressure of ~24 bars. This report presents a brief overview of the origins and purpose of the mission. Science objectives, entry parameters and mission events, and results are described. The remaining reports address in more detail the individual experiments summarized here.

The Galileo Entry Probe Mission to Jupiter conducted the first in situ measurements of the atmosphere of one of the outer giant planets. The information received from the probe defined the characteristics of the jovian atmosphere at the probe entry site to well below the visible clouds. The probe also defined the thermal structure of the upper atmosphere at the entry site during the high-speed entry phase of the probe mission. Even before sensing the atmosphere, probe instruments measured the inner radiation belts of Jupiter, a region of the magnetosphere that had not been previously sampled by any spacecraft and will not be sampled by the Galileo orbiter. In this report, we summarize the science objectives and technical aspects of the probe mission and briefly describe the major results.

The rationale for an entry probe mission to Jupiter arose in part from the inability to obtain sufficient information by remote sensing to adequately constrain models of formation and evolution of the outer planets. In particular, compositional and isotopic data regarding key trace species were lacking. On the basis of remote observations of Jupiter from Earth and from spacecraft, the mixing ratio of He was expected to be smaller in Jupiter than in the sun (*1*), whereas the mixing ratios of C, N, S, and O were expected to be larger in Jupiter than in the sun, perhaps by factors of two or three (*2–4*). The abundances of noble gases such as Ne, Kr, and Xe were unknown, as were their isotopic ratios (*2*). Other isotopic ratios of high interest, such as the D/H ratio, were subject to considerable uncertainty (*2*). The thermal structure of Jupiter's atmosphere at pressures much above 1 bar had not been measured, and only a few relatively imprecise temperature-pressure data points existed for the uppermost atmosphere. Three cloud layers were anticipated (*5*) on the basis of an approximately solar composition of the atmosphere. The existence of the lower two cloud layers—which had been predicted to consist of ammonium hydrosulfide and water aerosols, respectively—was inferred from modeling of spectroscopic data or comet Shoemaker-Levy 9 impact studies (*4*, *6*).

Major questions exist concerning the dynamic meteorology of Jupiter and the other large outer planets. One particularly important question is whether the global pattern of zonal winds observed on Jupiter, Saturn, Uranus, and Neptune (*7*) extends deep into their atmospheres or whether such winds are instead confined to cloud levels. The answer has implications for the energy source and driving mechanisms of the winds, and such a question could only be addressed by an entry probe.

The Galileo probe was designed and built by Hughes Space and Communications Group under contract to NASA Ames Research Center. The overall mission design and mission operations were the responsibility of the Jet Propulsion Laboratory. The Galileo probe and orbiter were launched on 18 October 1989 aboard the space shuttle Atlantis. Arrival date at Jupiter was 7 December 1995 (*8*).

Seven distinct science investigations were conducted from the Galileo probe (Table 1). In addition, two radio science experiments were performed: Doppler radio tracking of the probe from the Galileo orbiter, and a scintillation study of the probe-orbiter telemetry link. All probe science investigations successfully returned data (*9–16*). The Very Large Array (VLA) set of radio telescopes was also used in an independent effort to conduct Doppler tracking of the probe carrier frequency from Earth. It has now been verified that the probe carrier signal was successfully retrieved at the VLA, but results are still to be determined. The scintillation study of the probe-orbiter telemetry link had to wait for playback of data from the tape recorder on board the Galileo orbiter and will be reported on at a later date.

All probe entry parameters were close to nominal and were well within specifications (Table 2). The probe evidently entered the atmosphere either within or on the southern boundary of a localized atmospheric region known as a 5-μm hot spot (*17*). Such hot spots may have properties within and above cloud levels that differ from those of most of the atmosphere. However, probe measurements verified that below cloud levels, the variation of temperature with pressure was close to an adiabatic relation, as anticipated (*13*). Therefore, these deeper levels should be well mixed, and probe observations at these levels would be expected to be more representative of global conditions in the jovian atmosphere.

The probe instruments began direct sampling of the jovian atmosphere at 0.42 bar (Table 3). During approximately the previous 9 s, the instruments were active and exposed to the atmosphere because the aft heat cover had been jettisoned. However, as

Table 1. Probe investigations.

Investigation	Purpose	Principal investigator
Atmospheric structure instrument (ASI)	Thermal structure, vertical winds	A. Seiff, San Jose State University Foundation
Energetic particle detector (EPI)	Inner radiation belt parameters	H. Fischer, Universität Kiel
Lightning–radio emission detector (LRD)	Optical and radio lightning properties	L. Lanzerotti, Bell Laboratories, Lucent Technologies
Helium abundance detector (HAD)	Relative helium abundance	U. von Zahn, Universität Rostock
Nephelometer (NEP)	Cloud parameters, location	B. Ragent, San Jose State University Foundation
Net flux radiometer (NFR)	Solar-planetary radiative flux	L. Sromovsky, University of Wisconsin
Neutral mass spectrometer (NMS)	Composition (2 to 150 amu)	H. Niemann, Goddard Space Flight Center
Doppler wind experiment (DWE)	Zonal wind profile	D. Atkinson, University of Idaho
Radio scintillation experiment	Turbulence, signal absorption	R. Woo, Jet Propulsion Laboratory
Ground-based Doppler wind*	Zonal wind profile	R. Preston, Jet Propulsion Laboratory

*Not an originally selected Galileo investigation, but endorsed by the Galileo Project Steering Group.

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designed, the forward heat shield had not yet been jettisoned; thus, wake effects contaminated the measurements. The probe started direct atmospheric measurements 53 s (~0.3 bar) later than planned. The cause of this delay has been attributed to a fault in the wiring between the probe entry deceleration switches and the probe command processor. Measurements were apparently begun in the lower part of the top cloud layer, thought to consist of ammonia ice particles, rather than above the ammonia cloud, as planned (*12*). The solar zenith angle at the time of the start of direct measurements was ~68°.

The end of the probe signal occurred near the 24-bar pressure level, much deeper than the basic objective of 10 bars, at 61.4 min after entry. The probe maintained a telemetry link with the orbiter passing overhead for 57.6 min. Telemetry lock occurred 1 min after the beginning of descent mode operations and 35 s after the start of data transmission from the probe. Descent data acquired by the probe before telemetry lock were stored on board the probe and read out after telemetry lock had been established. Thus, an uninterrupted data stream covering 58.6 min was obtained from the beginning of descent. Energetic particle data obtained before entry and accelerometer data obtained during the high-speed deceleration phase of the probe mission were stored and transmitted during the descent phase. For consistency and ease of comparison between different instruments, all times are relative to the start of probe descent operation (Table 3).

The probe heat shield isolated the probe interior from the enormous entry heat loads. However, during parachute descent, environmental temperatures within the interior of the probe exceeded those predicted, both on the cold and warm sides. For example, the atmospheric structure instrument experienced hardware temperatures ranging from 30 K colder to 70 K warmer than the temperatures used in preflight calibrations. Other instruments experienced different temperature ranges, but all exceeded the expected ranges. In addition, the rate of change of temperature to which instruments and electronics were exposed exceeded the rates that had been predicted. Evidently, there was much closer thermal coupling of the interior of the probe to the jovian atmosphere than had been anticipated. This situation has necessitated efforts to recalibrate flight backup instruments within the encountered thermal environment and to perform additional data analyses. The results reported in this issue of *Science* reflect thermal corrections accomplished to date.

The Galileo probe results showed more He in Jupiter than was anticipated, with an abundance that was nearly solar (*9*, *10*); the abundance of C and S was about as expected, but that of O was far less than either its solar abundance or the expected amount (in the form of H_2O) (*10*). The mixing ratio of N in the form of NH_3 has not yet been determined. The noble gas abundances were found to vary markedly; Ne was greatly depleted with respect to its solar abundance, whereas Xe was greatly enriched (*10*). Isotopic ratios appeared to be nearly solar (*10*). No distinct water cloud was observed (*11*), but there was evidence of two upper cloud layers, corresponding to the expected positions of ammonia and ammonium hydrosulfide clouds (*11*, *12*). The thermal structure at the probe entry site was defined from pressures of $<10^{-8}$ bar to ~24 bars (*13*). The probe derived the vertical wind profile for Jupiter from just below the top cloud layer to about the 24-bar pressure level (*14*) and showed that zonal winds extend deep into the atmosphere. In addition, the probe determined the solar and planetary net radiative flux profiles in the atmosphere (*12*), characterized lightning within a few Earth diameters of the probe entry site (*15*), and discovered inner radiation belts consisting of He and heavier ions (*16*).

Table 2. Probe entry parameters (*18*). Longitude is referenced to System III.

Parameter	Target	Requirement	Achieved	Achieved uncertainty (1σ)
Entry time (UTC) at 450 km above 1-bar pressure level	22:04:26	±3 min	22:04:14	26 s
Relative flight path angle (degrees)	−8.60	−7.2 to −10.0	−8.38	0.05
Planetocentric latitude (degrees)	6.57°N	±6.6 (not within ±1) from equator	6.54°N	0.01
Longitude (degrees)	5.02°W	–	4.46°W	0.3

Table 3. Event timetable. Descent time is measured from beginning of probe descent operation. R_J, radius of Jupiter.

Descent time (min)	Pressure (bars)	Event
−187*	†	LRD/EPI data acquired at $5R_J$
−145*	†	LRD/EPI data acquired at $4R_J$
−106*	†	LRD/EPI data acquired at $3R_J$
−68*	†	LRD/EPI data acquired at $2R_J$; EPI continues until just after entry
−2.8	8×10^{-8}	Entry (450 km above 1-bar pressure level)
−1.82	0.006	Peak deceleration (228*g*)
0.0	0.41	Start of descent mode operation
0.058	0.41	Pilot chute deployed
0.079	0.41	Aft heat cover separated; main parachute deployed
0.23	0.42	Start of direct atmospheric measurements
1.0	0.53	Orbiter locks on to probe telemetry signal
3.4	1.0	Passage of 1-bar pressure level
32.5	10.0	Passage of 10-bar pressure level
58.6	24‡	End of probe signal

*To the nearest minute. †Below detectable limit. ‡Approximate value; all thermal corrections have not yet been determined.

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