Reports

The Galileo Venus Encounter

TORRENCE V. JOHNSON, CLAYNE M. YEATES, RICHARD YOUNG, JAMES DUNNE

The Galileo spacecraft passed Venus on its way to Jupiter on 10 February 1990, less than 4 months after launch from Earth aboard the shuttle Atlantis. Because Galileo's instruments were selected for broad-based planetary exploration, the spacecraft was able to obtain a wide range of measurements during the Venus encounter. Together with ground-based observations conducted during the encounter, these observations have yielded more accurate information about the planet's plasma environment, cloud patterns, and the possible existence of lightning.

INTENDED AS A MISSION TO EXPLORE the Jupiter system, Galileo was not originally designed with Earth's closer neighbor, Venus, in mind. However, following the Challenger accident in January 1986 NASA decided not to use the high-energy Centaur upper stage in the shuttle that was to carry the spacecraft. This left Galileo, which was already designed and fabricated, waiting at Kennedy Space Center (KSC) with no way to reach its goal. The problem was solved by finding trajectories with Venus and Earth gravity assists that could deliver Galileo to Jupiter on the lower energy Inertial Upper Stage (IUS) two-stage solid rocket, which had already been used in the shuttle (*1*). To take advantage of the opportunity afforded by the revised trajectory (Fig. 1) the instruments aboard Galileo were activated to acquire data on the atmospheric and plasma properties of Venus.

The umbrella-like antenna was originally designed to be opened after launch, but had to remain closed and pointed toward the sun, shielded by another shade mounted at the tip of the antenna, for the first portion of the flight inside 1 AU to prevent it from getting too hot (*2*). Because the high-gain antenna was unusable during this portion of the mission, two low-gain antennas were used, the original one at the top of the high-gain mast and an additional one added for communications when Earth is in the anti-sun hemisphere as viewed from the spacecraft (Fig. 2). Data rates were therefore much lower than for normal planetary missions. Even with the use of 70-m dishes of the Deep Space Network, rates were generally 1200 bits per second or lower, sometimes as low as 10 to 40 bits per second (compared with 134 kbits per second expected from Jupiter with the high-gain antenna).

The requirements for thermal protection of the spacecraft dictated the data acquisition at Venus. The sun-pointed spacecraft attitude constrained available viewing and target illumination geometries and the low real-time communications rates required that virtually all data collected be stored on the onboard digital tape recorder for playback when Galileo again came close enough to Earth for high rate communications (November 1990). Despite these limitations, an interesting set of observations were designed and successfully carried out during the Venus encounter. The first results of some of these investigations are contained in the set of reports in this issue, along with reports of some of the ground-based observations of the planet undertaken to complement and extend the spacecraft data.

Venus has been visited by numerous U.S. and Soviet spacecraft, flybys, orbiters, atmospheric probes and balloons, landers, and most recently by the highly successful Magellan radar mapping spacecraft. Given the limited data that could be collected from a Galileo flyby, planning for the Venus encounter concentrated on identifying those areas where Galileo observations could make the most significant contributions. Although not designed specifically for Venus, Galileo's instrument complement was selected to perform a broadly based exploration of a planetary system and thus contains state-of-the-art remote-sensing and space physics experiments, designed to study planetary surfaces, atmospheres, and space environments over a wide range of conditions. Some of these instruments are of types never used before on Venus spacecraft [such as the near-infrared mapping spectrometer (NIMS)]; others represent major improvements in instruments that have been used before [such as the CCD solid-state imaging system (SSI) and many of the space-physics experiments].

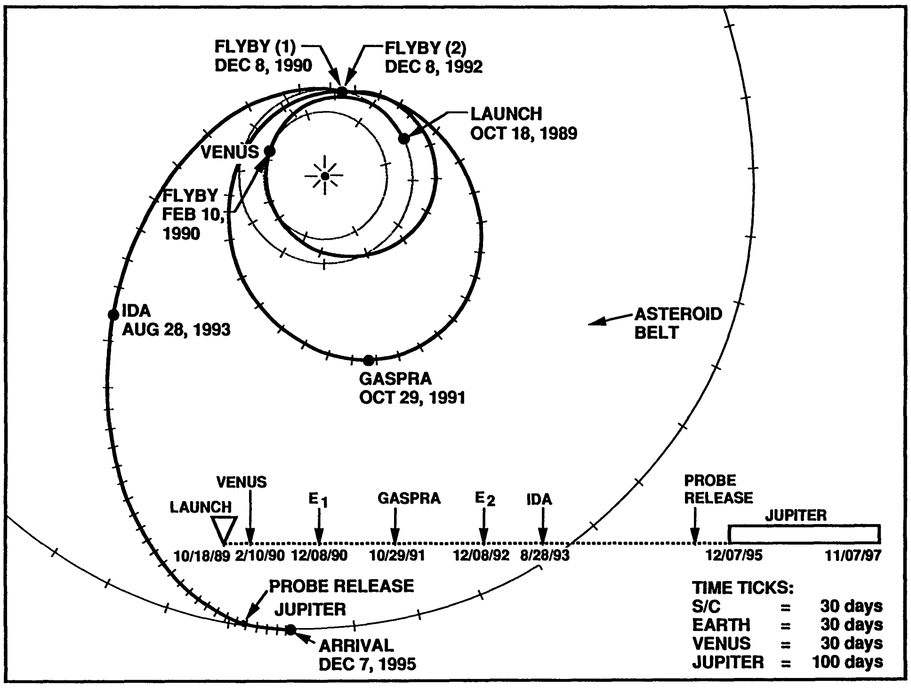

Fig. 1. The complete Venus-Earth-Earth gravity assist (VEEGA) trajectory of Galileo's mission to Jupiter. Key mission events are noted on a time line at the bottom of the figure; E_1 and E_2 are the first and second Earth flybys, respectively. Location of the spacecraft (S/C) is shown at 30-day intervals. Gaspra and Ida are asteroids.

T. V. Johnson, C. M. Yeates, J. Dunne, Jet Propulsion Laboratory, Pasadena, CA 91109.
R. Young, NASA Ames Research Center, Moffett Field, CA 94035.

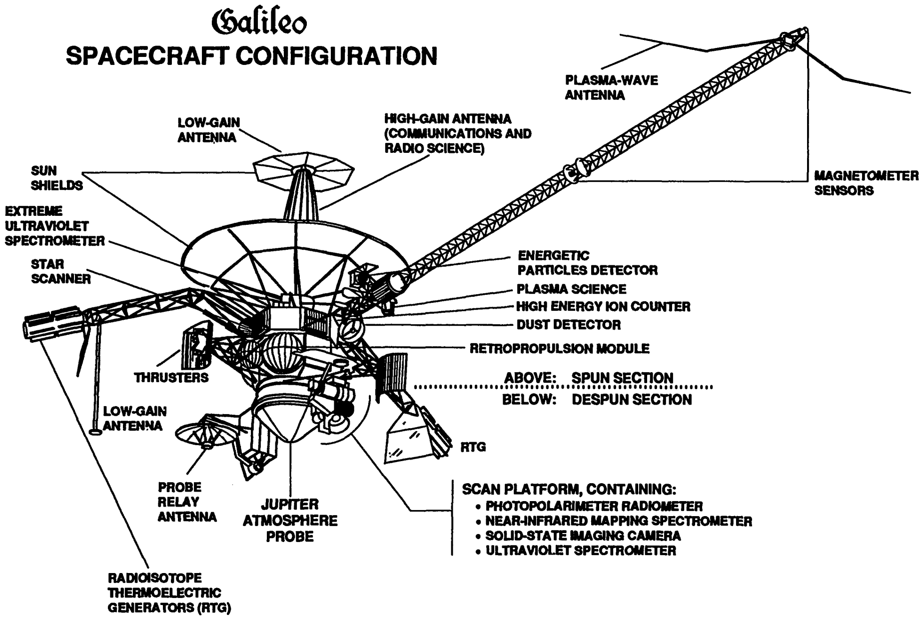

Fig. 2. Configuration of instruments on Galileo.

The planned observations fell into two general categories: (i) Observations best suited to Galileo capabilities or made for the first time and (ii) further study of phenomena observed by other spacecraft, including measurements in extended spectral ranges or under new geometrical conditions.

An example of the first category of observation is the series of night-side measurements planned by NIMS. Recent telescopic observations of Venus's night side have revealed that there are limited regions of the near-infrared spectrum where the combination of greenhouse gas absorptions in the atmosphere permit thermal radiation from the deep atmosphere to escape; observations at these wavelengths can thus probe the deep atmosphere of Venus, well below the visible clouds (*3*). Accordingly, NIMS obtained two partial-disk night-side maps at infrared wavelengths at resolutions three to six times better than Earth telescopic capabilities. Also in this category were the SSI high-spatial and temporal resolution tracking of small-scale ultraviolet features and the optical search for lightning. These observations, which will be described in more detail in the following reports, address fundamental questions regarding the dynamic meteorology, composition, and evolution of the Venus atmosphere.

Observations that were designed to extend previous measurements include ultraviolet spectra, limb haze studies, and many of the particles and fields experiments. Galileo was not expected to be in regions inside the solar-wind interaction with Venus; nevertheless a set of observations of magnetic fields, plasmas, and energetic particles were planned during the closest approach to look for phenomena that might be associated with Venus or its interaction with the solar wind. Analysis of the space-physics data showed that Galileo was in fact close enough to the interaction region and, due in part to the alignment of the interplanetary field at the time of encounter, was able to observe a number of interesting phenomena.

Another major use of Galileo's extended instrumentation capabilities and flyby geometry was the search by the plasma wave spectrometer (PWS) for electromagnetic waves associated with lightning. Interpretation of Pioneer Venus data suggesting Venus lightning has been a source of controversy for some years; Galileo's improved PWS frequency range and position outside the ionosphere allowed an independent search for lightning phenomena (*4*).

Venus first became "visible" to the remote sensing instruments on the scan platform some 17 hours before closest approach (Fig. 3), when the night side of the planet ceased being occulted by the spacecraft bus sun shade. At that time, a photopolarimeter radiometer (PPR) global dark-side map was obtained. These PPR radiometric observations continued from about −4 hours to near closest approach, interspersed with NIMS high-resolution spectra, partial disk images and night-side limb scans. About 45 min before closest approach, a dark-side lightning search was conducted by the SSI instrument. At closest approach, a number of high-resolution limb observations were made by the ultraviolet spectrometer (UVS), PPR, and NIMS. Between closest approach minus 2 hours 40 min and plus 40 min, the fields and particles (F&P) team looked for pickup ions (Venus ionospheric ions entrained in the solar wind), and the PWS acquired short high-frequency waveform samples in search of lightning signatures as discussed above. As the spacecraft departed with the day side of Venus in view, a series of SSI observations were conducted over the next several days. The first of these was a high resolution (0.5 to 1.8 km per pixel) limb haze study made with the violet and near-infrared filters. This was followed

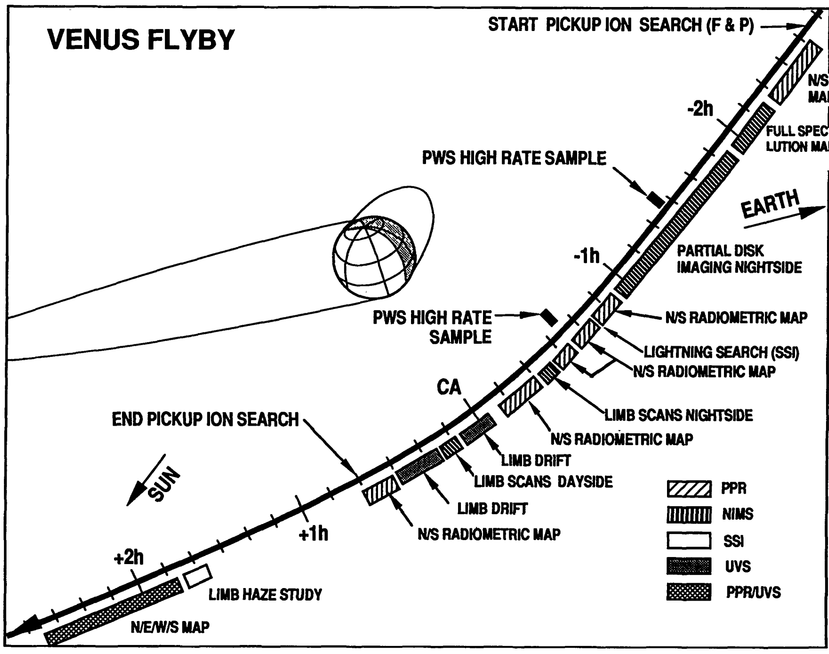

Fig. 3. Detailed time line of Galileo's encounter with Venus. The point of closest approach is labeled CA. Instrument designations are given in the text.

by a 30-hour small-scale (6 to 20 km per pixel) "feature track" imaged through violet filters to monitor a patch of cloud deck from "morning" to "afternoon" across the face of the planet. Next, the departure portion of the lightning search was conducted, looking at the terminator/dark limb, searching a larger area and a different longitude region than on the approach. The final sequence was a series of images taken during the next 6 days to study the dynamics of the clouds visible in short wavelength (violet) images and look for structure in dayside near-infrared (~1 μm) pictures.

REFERENCES AND NOTES

1. L. A. D'Amario, D. V. Byrnes, J. R. Johannesen, B. G. Nolan, paper presented at the American Astronomical Society/American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference, Kalispell, Montana, August 1987.
2. Subsequent to the first Earth flyby in December 1990, an attempt was made to deploy the main antenna which resulted in only partial deployment. As of this writing, analysis is still under way to determine the cause of the problem and correct it.
3. D. Allen and J. W. Crawford, *Nature* **307**, 222 (1984); D. Allen, *Icarus* **69**, 221 (1986); D. Crisp *et al.*, *Science* **246**, 506 (1989).
4. C. T. Russell [*Space Sci. Rev.* **55**, 317 (1991)] has a review of the controversy and recent references.
5. One the authors of this paper, Dr. Clayne Yeates, tragically died in April 1991. As Science Manager and later Science and Mission Design Manager on Galileo, he was a principal architect of the observational strategy at Venus and the entire Galileo science community acknowledges their deep appreciation for his contributions and their grief at his loss. This paper represents work carried out at Jet Propulsion Laboratory/California Institute of Technology under a contract with NASA.

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Magnetic Field Studies of the Solar Wind Interaction with Venus from the Galileo Flyby

M. G. Kivelson, C. F. Kennel, R. L. McPherron, C. T. Russell, D. J. Southwood, R. J. Walker, C. M. Hammond, K. K. Khurana, R. J. Strangeway, P. J. Coleman

During the 10 February 1990 flyby of Venus, the Galileo spacecraft skimmed the downstream flank of the planetary bow shock. This provided an opportunity to examine both the global and the local structure of the shock in an interval during which conditions in the solar wind plasma were quite steady. The data show that the cross section of the shock in planes transverse to the flow is smaller in directions aligned with the projection of the interplanetary magnetic field than in directions not so aligned. Ultralow-frequency waves were present in the unshocked solar wind, and their amplitude peaked when the spacecraft was downstream of the foreshock. At large distances down the tail, the Mach number of the flow normal to the shock is low, thus providing the opportunity to study repeated crossings of the collisionless shock in an interesting parameter regime. Some of the shock crossings reveal structure that comes close to the theoretically predicted form of intermediate shocks, whose existence in collisionless plasmas has not been confirmed.

Galileo flew by Venus on its lengthy interplanetary voyage toward Jupiter. The spacecraft approached the planet from the downstream direction (Fig. 1) and skimmed the planetary bow shock, repeatedly traversing it as it passed down the Venus wake (*1*). During an interval of several hours (limited by spacecraft tape-recorder resources), the magnetometer acquired unique data on the shock and the solar wind immediately upstream of the shock. The unusual approach trajectory provided the opportunity to observe several quasi-parallel bow shock crossings with exceptionally low Mach number, to investigate dynamical changes of the large-scale shock geometry, and to study the upstream magnetohydrodynamic (MHD) waves and investigate aspects of their generation.

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

Magnetic field data (Fig. 2) were obtained by the fluxgate magnetometer (*2, 3*) from 0100 to 0700 universal time (UT) at the spacecraft (that is, spacecraft event time). The evidence of shock crossings is obtained initially from inspection of the plotted data, which contains multiple steps across which the field magnitude increases or decreases abruptly with little change apparent between successive entries into either regime. This pattern is characteristic of crossings of a bow shock that moves back and forth over a spacecraft. Table 1 lists the times of the clear shock crossings. Confirmation that the sharp changes in the total magnetic field B_T truly correspond to shocks has been provided by the Galileo Plasma System (*4*), which reveals electron heating across the apparent shocks identified by the magnetometer, and by the Galileo Plasma Wave System (*5*), which identified broadband radiation characteristic of shock crossings during the two shock pairs (labeled A and B in Fig. 2 and in Table 1) for which their broadband data were available. If one estimates the strength of the shock in terms of the ratio of the downstream to upstream field magnitudes, all of the shocks are weak, but they increase in strength as the spacecraft approaches the planet.

A stationary bow shock would normally intersect the trajectory at most twice, yet on 10 February 1990 the shock swept back and forth over the spacecraft many times. As the position of a planetary bow shock is governed by the fast magnetosonic Mach number of the solar wind, fluctuations of plasma parameters can cause displacements of the shock and thus account for the repeated crossings. However, the Galileo data show relatively minor changes in the magnitude of the magnetic field, and intermittent values for the solar wind speed, density, and ion temperature (*6*) from the Pioneer Venus Orbiter (PVO) plasma analyzer (*7*) show only small changes during the interval of interest. The field orientation, on the other hand, appears to rotate before almost every crossing from the solar wind to the bow shock, providing a clue to the reason for the multiple crossings.

In a study of PVO shock crossing locations in planes transverse to the flow, Russell *et al.* (*8*) found that the cross section of the shock is slightly noncircular, with the ellipticity (the ratio of the major to the minor axis) largest for cone angles [the angle between the interplanetary magnetic field (IMF) and the VSO–X axis] of 90°. Finding a tendency for the shock to lie closer to the symmetry axis in directions aligned with the YZ–VSO projection of the IMF, they attributed the ellipticity to the anisotropy of the fast mode wave speed. For cone angles near 90°, they show a fit to an ellipse with ellipticity of ~1.11.

With these earlier results in mind, we investigated whether the multiple crossings of the shock can be explained on the assumption that a slightly flattened shock surface of changing ellipticity reorients itself about the VSO–X direction under control of the IMF. We adopted a simple approximation based on the concept of a Mach "cone" originating in a circle of radius 3.4 R_V from the center of Venus in the terminator plane. The flaring angle θ_{MF} satisfies

$$\sin(\theta_{MF}) = 1/M_F(\theta_{Bn}) \qquad (1)$$

Here $M_F = v/c_F\ (\theta_{Bn})$ is the fast magnetosonic Mach number, the ratio of v, the solar