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.

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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

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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.

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

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

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

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wind flow velocity, to the fast magnetosonic phase speed c_F, which is itself a function of θ_{Bn}, the angle between the IMF and the normal to the shock. As θ_{MF} varies with θ_{Bn}, the cross section becomes quasi-elliptical in the antisolar direction. In calculating c_F, we set the Alfvén speed c_A = 73 km/s and take

$$\beta = p/(B^2/2\mu_0) = (2/\gamma)(c_s^2/c_A^2) = 1.73 \quad (2)$$

where β is the ratio of the thermal pressure to the magnetic pressure, p is the thermal pressure, B is the magnetic field, μ_o is the permeability of free space, γ is the polytropic index, and c_s is the speed of sound.

The solar wind flow velocity was taken to be 430 km/s based on the PVO data mentioned above. The assumption that the origin is at a fixed radius of 3.4 R_V in the terminator plane was based on simulations of gas-dynamic shocks for conditions at Venus. From figure 8 of Slavin *et al.* (*9*), we find that asymptotes to the shocks cross each other at approximately this distance at X = 0 independent of Mach number. The shock itself crosses the X = 0 plane closer to the planet.

This simple model allows us to calculate the distance (along the normal) between Galileo and the shock as a function of the IMF measured at the spacecraft (Fig. 3). The zero crossings of the distance parameter correspond closely to times of shock crossings.

The Galileo trajectory and the location of the model shock in the plane containing the spacecraft and the X axis are shown in Fig. 4. The shock crossings usually occur as the θ_{Bn} of the upstream field rotates toward 90°. For $X < -4\ R_V$, the model predicts the shock crossings accurately. The maximum ellipticity in this model (ratio of the major to the minor axis for 90° cone angles) is of order 1.1, that is, roughly the same as in the terminator plane. The fact that each distant shock crossing observed by Galileo took place while a rotation of the magnetic field was in progress suggests that the relation found by Russell *et al.* (*8*) also applies to individual, short time scale rotations of the IMF. In other words, the magnetosonic Mach angle of the distant shock reflects the dependence of the fast MHD wave speed on the direction of the magnetic field.

It was not apparent to us that an asymptotic linear model would work so well at distances between ~4 and 10 R_V downstream of Venus. In particular, it is clear from the presence of the field compression at the shock crossings that the spacecraft was not in the true asymptotic regime, for which the magnetosonic Mach number calculated from the normal flow velocity is 1. (As the asymptotic conditions have not been met, θ_{Bn} gives an underestimate of M_F and an overestimate of β in the upstream solar wind.)

A full shock model can be constructed by matching a hyperbolic fit of the form given by Slavin *et al.* (*9*) to the asymptotic form found in our analysis. Details of the fit parameters will be provided elsewhere (*10*).

The flattening of the shock cross section is also expected to occur at Earth but would be harder to identify because of the great difference in spatial scale. Because Venus has no magnetosphere, the distance of its bow shock from the center of the planet at the

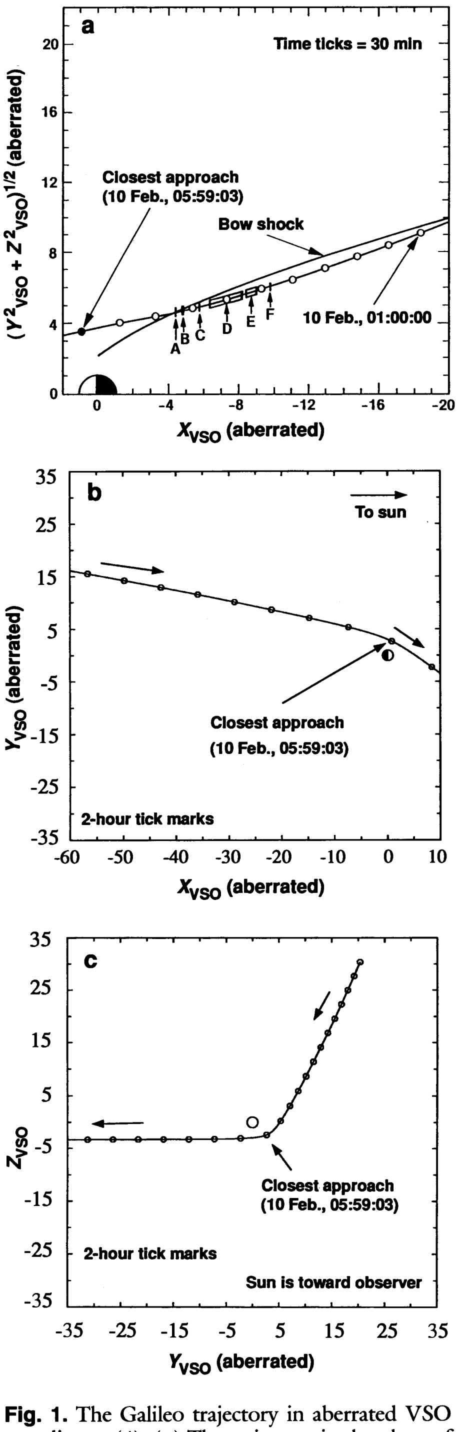

Fig. 1. The Galileo trajectory in aberrated VSO coordinates (*1*). (**a**) The trajectory in the plane of the spacecraft in terms of distance along the (aberrated) planet-sun line and perpendicular distance from that line. A crude shock model is also shown, and locations of observed shock crossings are indicated and labeled with letters from A to F. (**b** and **c**) The trajectories in the aberrated X-Y and Y-Z planes, respectively.

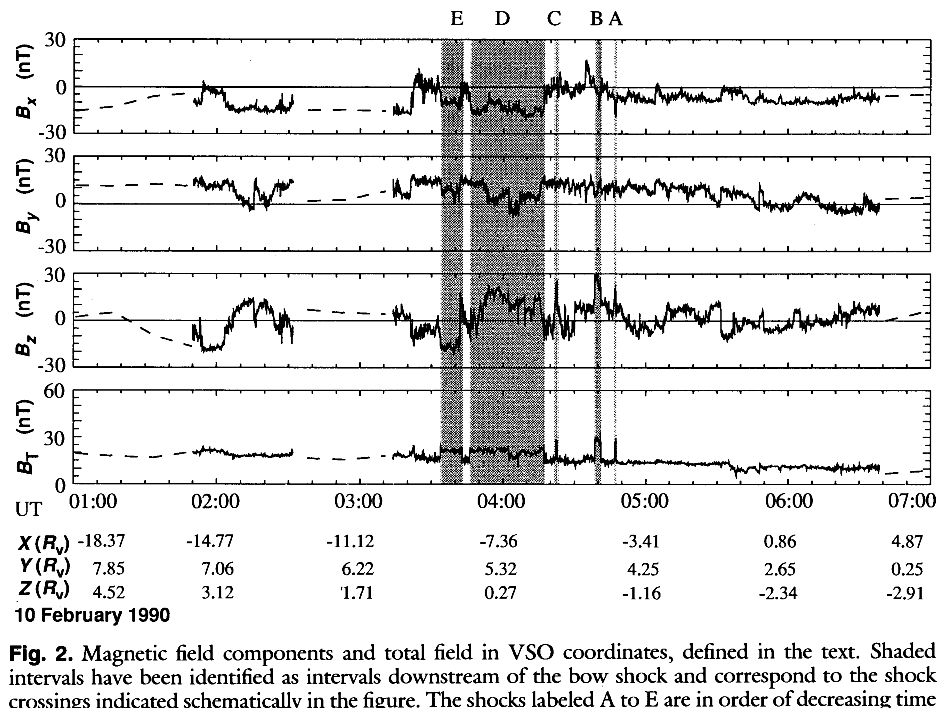

Fig. 2. Magnetic field components and total field in VSO coordinates, defined in the text. Shaded intervals have been identified as intervals downstream of the bow shock and correspond to the shock crossings indicated schematically in the figure. The shocks labeled A to E are in order of decreasing time on this plot. Gaps in the full-time-resolution data have been filled in with 16-min time resolution data.

Table 1. Times of Venus shock encounters and directions of crossings. SW, solar wind; M, magnetosheath.

Direction of crossing	Designation on figures and in text	UT of crossing	VSO X (R_V)	VSO Y (R_V)	VSO Z (R_V)
SW to M	E-2	03:33:43	−9.0	5.9	1.2
M to SW	E-1	03:43:00	−8.4	5.6	0.7
SW to M	D-2	03:46:00	−8.2	5.2	0.6
M to SW	D-1	04:17:33	−6.3	5.0	−0.1
SW to M	C-2	04:22:12	−5.9	5.0	−0.2
M to SW	C-1	04:22:55	−5.9	4.9	−0.3
SW to M	B-2	04:38:40	−4.8	4.7	−0.7
M to SW	B-1	04:41:09	−4.7	4.6	−0.7
SW to M	A-2	04:46:57	−4.3	4.5	−0.8
M to SW	A-1	04:47:44	−4.2	4.5	−0.9

subsolar point is approximately 1 R_V. The shock surface comes close to its asymptotic Mach cone at distances of about 10 R_V downstream. It takes the solar wind about 3 min to flow from the front of the shock to this distance downstream, so Venus's asymptotic shock will adjust to variations in the upstream solar wind within minutes. By contrast, the nose of Earth's magnetopause lies at about 10 R_E, so simple scaling arguments suggest that the asymptotic shock is approached only beyond 100 R_E downstream. The flow time from the nose to the distant shock is about 30 min, not small on the time scale of IMF fluctuations. Furthermore, the differing tail structures of an intrinsic magnetosphere with field lines rooted in the planet and an induced magnetosphere with field lines borrowed from the solar wind may invalidate simple scaling arguments. Thus, spacecraft measurements near Earth might not reveal the asymmetry of the quasi-asymptotic shock region as unambiguously as do these Galileo measurements from Venus.

During intervals in the solar wind (unshaded portions in Figs. 2 and 3), large amplitude fluctuations in B_T are evident. The frequencies peak in the ~10- to 50-mHz band. This type of upstream wave activity is typical within the quasi-parallel regions of planetary bow shocks [see, for example, (*11*)]. The appearance of upstream waves is associated with the presence of particles streaming away from the planetary bow shock along the IMF. Spatial regions in which field lines are connected to the shock are bounded upstream by a surface called the foreshock. The position of the foreshock in a plane containing the solar wind streamline through a spacecraft is defined by the IMF line tangent to the bow shock. (Evidently, for some IMF orientations there is no such tangent.) If the foreshock can be defined, the distance along the tangent field line to the intercept of the streamline (distance) and the distance along the streamline to the intercept (depth) characterize the spacecraft's position relative to it.

In the region near Venus, an elliptical fit to the X–ρ cross section of the shock (*12*) is superior to a hyperbolic fit. Consequently, for the analysis of the foreshock, we fit an ellipse (ellipticity, eps, 0.96, offset 0.4 R_V, with semi-latus rectum $L = 2.009\ R_V$, symmetric transverse to the flow) to the Galileo shock encounters. During most of the time that large fluctuations appear in the magnetic field upstream of the shock in Figs. 2 and 3, Galileo was downstream of the foreshock (Fig. 5).

The data and the model provided here are relevant to the interpretation of the fluxes of energetic ions observed upstream of the shock (*13*). The analysis of the magnetic fluctuations suggests that the power in the upstream waves was slightly enhanced when the energetic particle fluxes were present.

The data provide insight into the local as well as the global structure of the shock. The theoretical analysis of the local structure of MHD shocks derives from the pioneering work of de Hoffmann and Teller (*14*). The Rankine-Hugoniot relations, conditions that express the conservation of mass, momentum, and energy across the shock, have six solutions (*15, 16*). In characterizing the solutions that satisfy the Rankine-Hugoniot conditions, it is convenient to classify normal flow velocities by their relation to the phase velocities of the wave modes. Class 1 flows are superfast; class 2 flows are subfast but superintermediate; class 3 flows are subintermediate but superslow; and class 4 flows are subslow. Shocks can be classified by the flows that bound them (*17*). The four additional "intermediate shock" solutions to the Rankine-Hugoniot relations that take the flow from superintermediate to subintermediate are of the type (1,3), (1,4), (2,3), or (2,4). All require that the component of the magnetic field along the shock surface change sign across the shock (*15*). Switch-on and switch-off shocks, in which the tangential component of the magnetic field vanishes on one side of the shock (but not both), are degenerate cases. The usual fast- and slow-mode shocks change the magnitude of the component of the magnetic field in the shock plane but do not change its sign.

Arguments that these additional solutions involving the intermediate mode velocity are extraneous and intrinsically unstable [see, for example, the "evolutionary" arguments of Kantrowitz and Petschek (*18*)] inhibited extensive investigation of their properties. However, interest in the study of intermediate shocks has been reawakened by the work of Wu (*19, 20*), who found that intermediate shocks arise in numerical solutions of resistive MHD equations through nonlinear steepening of a continuous wave. Kennel *et al.* (*15*) showed that solutions of the intermediate shock type can arise only for a restricted range of upstream flow con-

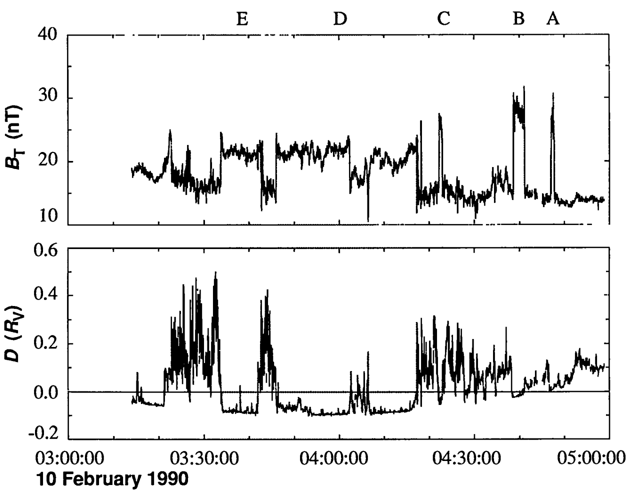

Fig. 3. The lower panel shows the distance from the bow shock measured along the shock normal, calculated as described in the text from measured magnetic field orientations versus UT. Distances are shown as positive or negative depending on whether the model indicates that the spacecraft is in the solar wind or in the magnetosheath, respectively. The distance estimates are not meaningful in the shaded regions when the spacecraft is within the magnetosheath, as the orientation of the IMF is not known. The top panel shows the measured total magnetic field, B_T. The intervals downstream of the shock (B_T enhanced) and the intervals of negative distance correspond extremely well.

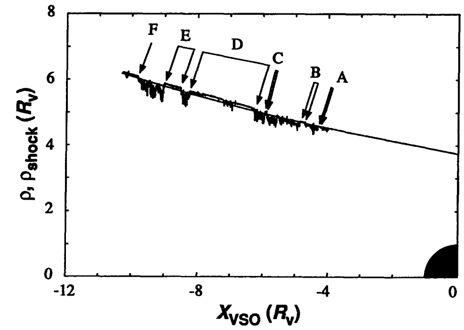

Fig. 4. A plot of the spacecraft trajectory in the X–ρ plane [where $\rho = (y^2 + Z^2)^{1/2}$ and the aberrated VSO coordinates are used] and the modeled position of the downtail shock based on locally measured values of the magnetic field. The asymptotic shock surface is not plotted at distances closer than $X = -4\ R_V$. Locations of observed shocks are indicated with arrows and labeled as in Table 1.

ditions. Critical parameters of the flow are the plasma β, γ (here taken to be 5/3), and the Alfvén Mach number, $M_A = v/c_A$. For (1,3) or (1,4) shocks at small β, that is, $\beta < 1$, the upstream flow must have $1 < M_A < 2$, and, as β increases, the cutoff comes for smaller M_A. The limitations are not typical of day-side planetary bow shocks. For example, on the day side of Earth, where the solar wind flows at relatively small angles to the shock normal, the typical M_A is close to 6. Furthermore, the normal to the shock must be nearly field-aligned (that is, the shocks must be nearly parallel shocks). When the sound speed exceeds the Alfvén speed upstream ($\beta > 2/\gamma$), intermediate shocks of types (1,3) and (1,4) cannot exist, but those of type (2,3) and (2,4) continue to do so. We expect that shocks of types (1,3) and (1,4) might be part of the bow shock whereas those of types (2,3) and (2,4) will separate from a fast shock.

At Venus, as at Earth, the nominal dayside M_A is close to 6. However, Galileo skimmed the downstream flank of the Venus bow shock where the solar wind flows at a small angle to the shock front, and the M_A based on the normal component of the flow velocity and various shock models (*8, 9, 12*) decreases to values below 2. Fortuitously, during the flyby the IMF had a very small component along the planet-sun direction and was nearly aligned with the shock normal for some of the shock encounters. Thus, the shocks in most cases also satisfied the quasi-parallel condition (that is, θ_{Bn} was less than 45°).

Not only were the shock parameters within the range required for the development of an intermediate shock, but also some of the shock crossings revealed the change of sign of the transverse component of the magnetic field required in an intermediate shock. In particular, large rotations occur just downstream of the shocks at 03:43 and at 04:17. (Time reads backwards in Fig. 2, going from upstream to downstream for these two outbound shock crossings.) The decrease of B_T during the outbound crossing from approximately 03:42:50 to 03:43:15 is consistent with a fast shock. Downstream of the compression at approximately 03:41:55, the field rotated abruptly (evident in Fig. 2 principally as a sign change of B_z); the field magnitude dipped briefly during the rotation. The plane of the shock can be determined from an analysis to be described elsewhere (*21*), and the component of the field in the shock plane changed sign. This sign change is consistent not with a fast shock but with an intermediate shock. The associated brief change of field magnitude is not expected in a rotational discontinuity but is a feature of the intermediate shock (*22*).

The observed sign change of the transverse component of the magnetic field downstream of the shock suggests that Galileo crossed an intermediate shock. However, it is possible that the association of a field rotation with the shock was accidental and that the rotation was merely convected through the fast shock as the solar wind plasma crossed into the magnetosheath. Indeed, a field rotation was observed at PVO (which at this time was in the magnetosheath and provided measurements of the VSO–Z component) just 84 s before the field at Galileo rotated. The time delay is consistent with the separation (8 R_V in X–VSO) of the two spacecraft and the observed solar wind speed for a somewhat tilted orientation of the front. However, the change of the VSO–Z component occurred more rapidly at Galileo than at PVO. It is natural for the spatial extent of a rotational discontinuity to expand or compress as the velocity of the fluid changes. However, a slower downstream flow velocity carries the compressed signature over a spacecraft more slowly and the two effects cancel. Thus, pure convection across a fast mode shock and within the magnetosheath should not cause the time series measurements of a rotational discontinuity to steepen, and the PVO signature taken downstream of a fast mode shock should differ little in time scale from the solar wind signature. Unless other processes are producing changes in the signature, the steepening observed in the Galileo data suggests that Galileo did not observe a simple rotational discontinuity that crossed into the magnetosheath through a standard fast shock but more probably observed an intermediate shock. This would be consistent with the simulation results of Wu (*23*), which suggest that upstream rotational discontinuities propagating through a preexisting fast shock with low Mach number can under the appropriate conditions steepen into intermediate shocks.

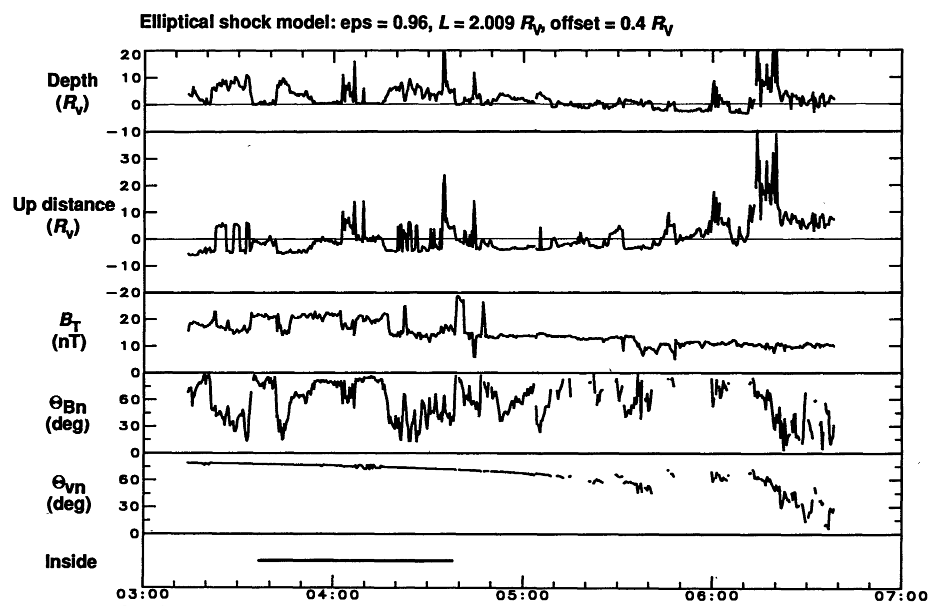

Fig. 5. Plot of depth and distance relative to the modeled foreshock boundary. From the top, the panels are depth and distance, 1-min averages of the total magnetic field, and the angles θ_{Bn} (the angle between the magnetic field and the model shock normal at the point where the field line at the spacecraft intersects the model shock) and θ_{vn} (the angle between the aberrated solar wind velocity and the model normal at the point of intersection). When the spacecraft is antisunward of the foreshock, depth is negative by convention. Distance is positive in the antisunward direction from the tangent point and negative in the sunward direction. The black bar in the bottom panel identifies the portion of the data during which the trajectory was within the model shock, thus invalidating the model analysis.

A rotation in the downstream field is also observed in the shock occurring at 04:17. At this time the PVO spacecraft was upstream of Galileo and in the solar wind. At Galileo, there were two rotations of the field just downstream of the fast mode compression of the field. There was a dip in field magnitude associated with each of the rotations, but the downstream field returned to its original upstream position after them. There was no clear signature of these rotations of the field in the upstream field as measured by PVO. As in shock E-1, there was a decrease in the magnitude of the field associated with the rotation. The component of the field in the shock surface rotated through roughly 720°, which is considerably different from the rotation at 03:42 UT in shock E-1.

These shock crossings may provide the first evidence that intermediate shocks can develop in a collisionless plasma. It is difficult to establish unambiguously that a compression closely associated with a change of the sign of the shock-plane component of the magnetic field is actually an intermediate shock. Elsewhere (*21*), we demonstrate that the measured field changes across the 03:43 shock crossings fall into the parameter regime required for an intermediate shock and that the 04:17 shock has a structure that we characterize as "exotic" and different from the expected form of either a fast or an intermediate shock. Because the field is variable, the analysis is not unambiguous but the results are highly suggestive of the rich and diverse shock physics we may find on further analysis of this remarkable data set. Further evidence concerning the nature of these two and other shocks will come from comparison with data from the plasma instrument on Galileo. It will be of particular interest to search for changes in density and temperature and to evaluate the anisotropy of the plasma pressure, which can modify the properties of the rotational discontinuity.

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Lightning and Plasma Wave Observations from the Galileo Flyby of Venus

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During the Galileo flyby of Venus the plasma wave instrument was used to search for impulsive radio signals from lightning and to investigate locally generated plasma waves. A total of nine events were detected in the frequency range from 100 kilohertz to 5.6 megahertz. Although the signals are weak, lightning is the only known source of these signals. Near the bow shock two types of locally generated plasma waves were observed, low-frequency electromagnetic waves from about 5 to 50 hertz and electron plasma oscillation at about 45 kilohertz. The plasma oscillations have considerable fine structure, possibly because of the formation of soliton-like wave packets.

The occurrence of lightning in the atmosphere of Venus has been reported by several investigators but still remains controversial. The existence of lightning at Venus is important because it is indicative of convective storms in the atmosphere. Also, lightning may be an indicator of active volcanism. The previous reports of lightning at Venus include various measurements of impulsive low-frequency (<80 kHz) radio signals from the Venera landers (*1*) and observations of very low-frequency (~100 Hz) whistler signals from the Pioneer-Venus orbiter (*2*). For the Venera data there has always been a concern that the signals could have been caused by locally induced electrostatic discharges as the spacecraft descended through the atmosphere, and for the Pioneer-Venus data the whistler interpretation has been criticized on the grounds that the signals could have been caused by various types of locally generated plasma waves (*3*). The Galileo observations now provide strong evidence that lightning does exist in the atmosphere of Venus.

The Galileo flyby of Venus provided an excellent opportunity to search for radio signals from lightning. As described by Gurnett *et al.* (*4*), the Galileo plasma wave

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