plasma oscillations can be seen, one consisting of a weak, nearly steady line at a frequency of about 45 kHz, which we identify as the electron plasma frequency, f_{pe} (see Fig. 3), and a second that is primarily shifted downward from the local electron plasma frequency. The downshifted component appears to be similar to the downshifted electron plasma oscillations observed upstream of the Earth's bow shock (*10*). These waves are almost certainly produced by suprathermal electrons streaming into the solar wind from the bow shock. The electron plasma oscillations abruptly stop at about 0512 UT. This termination probably represents a crossing of the electron foreshock boundary. The foreshock is a region of the solar wind that is magnetically connected to the bow shock. Beyond the foreshock, plasma oscillations cannot be excited because suprathermal electrons can no longer reach the spacecraft.

Near the end of the spectrogram, at about 0524 UT, a brief burst of electron plasma oscillations can be seen around 40 kHz. This burst probably represents a brief contact with the electron foreshock, most likely due to changes in the orientation of the solar wind magnetic field. By chance, a 78-s high-rate waveform frame was scheduled at almost exactly this time. These measurements give very high-rate samples of the electric field waveform at 201,600 samples per second, thereby providing high-resolution spectra of the waves that occurred in this region (Fig. 4). The plasma oscillations have a considerable amount of fine structure. A weak emission line can be seen at about 43 kHz. This frequency is probably the local electron plasma frequency. Large shifts, both upward and downward in frequency by as much as 20 kHz, are clearly evident. Also, the oscillations break up into intense, nearly monochromatic packets lasting only a fraction of a second. These highly structured emissions are strongly suggestive of soliton-like structures, which have been widely predicted by various theoretical studies (*11*).

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12. We thank the Galileo project team at NASA Headquarters and at the Jet Propulsion Laboratory (JPL) for their valuable support in carrying out this investigation. We also thank L. Granroth, S. Allendorf, and B. Waggoner of the University of Iowa and C. de Villedary of Centre National d'Etudes des Telecommunications/Centre de Recherches in Physique de l'Environnement for their efforts in processing the data, and we acknowledge the valuable contributions of the late R. R. Shaw, F. L. Scarf, and S. D. Shawhan, who were co-workers on this investigation. The research at the University of Iowa was supported by NASA through contract 958779 with JPL.

26 April 1991; accepted 1 July 1991

Energetic Particles at Venus: Galileo Results

D. J. Williams, R. W. McEntire, S. M. Krimigis, E. C. Roelof, S. Jaskulek, B. Tossman, B. Wilken, W. Stüdemann, T. P. Armstrong, T. A. Fritz, L. J. Lanzerotti, J. G. Roederer

At Venus the Energetic Particles Detector (EPD) on the Galileo spacecraft measured the differential energy spectra and angular distributions of ions ≥22 kiloelectron volts (keV) and electrons ≥15 keV in energy. The only time particles were observed by EPD was in a series of episodic events [~0546 to 0638 universal time (UT)] near closest approach (0559:03 UT). Angular distributions were highly anisotropic, ordered by the magnetic field, and showed ions arriving from the hemisphere containing Venus and its bow shock. The spectra showed a power law form with intensities observed into the 120- to 280-keV range. Comparisons with model bow shock calculations show that these energetic ions are associated with the venusian foreshock–bow shock region. Shock-drift acceleration in the venusian bow shock seems the most likely process responsible for the observed ions.

A major event in the more than 6-year journey of the Galileo spacecraft to Jupiter was its encounter with Venus on 10 February 1990. The encounter provided an opportunity to observe the Venus environment, and we report here results from the EPD on Galileo during the Venus flyby. These results represent the initial observations of energetic ions at Venus, because previous particle detectors flown by the planet did not cover the energy range over which we report ion measurements, ~22 to 280 keV.

The EPD measures the fluxes, spectra, and angular distributions of ions ≥20 keV, electrons ≥15 keV, and elemental species (He through Fe) ≥10 keV per nucleon. The Low Energy Magnetospheric Measurement System (LEMMS) uses magnetic separation and absorber foils to provide the ion and electron measurements. The Composition Measurement System (CMS) uses $\Delta E \times E$ and time-of-flight techniques to provide the elemental species measurements. The two bidirectional detector heads, LEMMS and CMS, are mounted on a platform that can be rotated 180° by a stepper motor. This motion, coupled with the spacecraft spin, provides an angular coverage of a full 4π Sr. A complete description of the EPD can be found in the report by Williams *et al.* (*1*).

Galileo operational constraints at Venus limited the use of the EPD to the following observational mode: (i) only the LEMMS detector head was activated, and (ii) angular distributions were obtained only in the plane perpendicular to the Galileo spin axis (which was pointed away from the sun). The resulting data were received at Earth when the tape recorder was played back on 19 November 1990, more than 9 months after the encounter.

The Galileo trajectory by Venus has been presented in the report by Johnson *et al.* (*2*). To place an appropriate perspective on the EPD observations, we show at the bottom of Fig. 1 the Galileo trajectory by Venus and a model bow shock for comparison. The EPD obtained angular scans in the plane perpendicular to the spacecraft spin axis,

D. J. Williams, R. W. McEntire, S. M. Krimigis, E. C. Roelof, S. Jaskulek, B. Tossman, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.
B. Wilken and W. Stüdemann (deceased), Max Planck Institute für Aeronomie, Katlenburg-Lindau, Federal Republic of Germany.
T. P. Armstrong, University of Kansas, Lawrence, KS 66044.
T. A. Fritz, Los Alamos National Laboratory, Los Alamos, NM 87545.
L. J. Lanzerotti, AT&T Bell Laboratories, Murray Hill, NJ 07974.
J. G. Roederer, University of Alaska, Fairbanks, AK 99775.

which is indicated in the figure. Data were recorded from the EPD from ~0310 to 0835 UT with a data gap from ~0638 to 0738 UT. The intervals of energetic ion (≳22 keV) fluxes observed by EPD are indicated as solid bars along the trajectory time line. At no time were electrons (≳15 keV) observed and at no other times were energetic ions observed, including the ~0336 to 0438 UT interval when Galileo was encountering or was inside the venusian bow shock [see Kivelson *et al.* (*3*) and Frank *et al.* (*4*)].

Two types of EPD response are evident (Fig. 1): first, through the interval 0545 to 0601 UT there is a slow, continuous rise in the lowest energy channel (22 to 42 keV) to a maximum intensity followed by falloff; and second, there are a series of impulsive appearing events extending to higher energies. The first type of event occurs only once and displays an anisotropy sharply peaked in the direction of Venus. We interpret this response as due to solar photons that are scattered from the sunlit hemisphere of Venus and penetrate the thin (15 μg/cm^2) front aluminum coating of the LEMMS solid-state detector in sufficient numbers to excite the lowest electronic energy threshold. The timing of this event coincides with the EPD-LEMMS field of view sweeping the sunlit hemisphere of Venus (Fig. 1) and thus supports this interpretation.

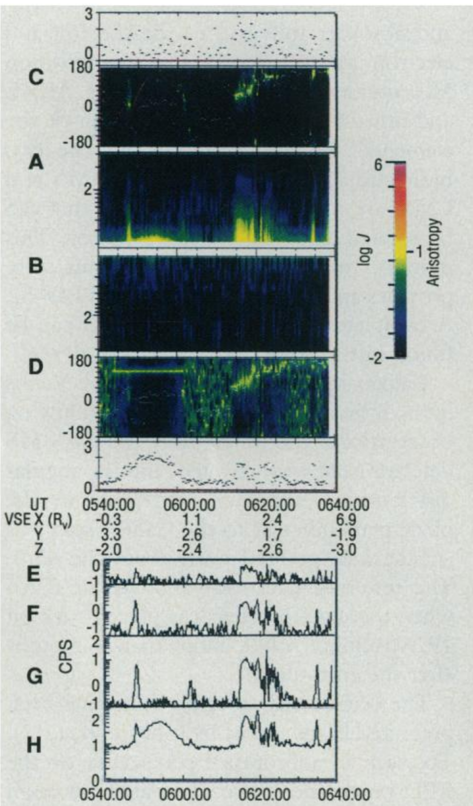
In contrast, the impulsive appearing events shown in Fig. 1 all extend to higher energies, display a much broader angular response than that due to the venusian scattered photons, and show anisotropies that are ordered by the magnetic field. This latter property is evident in Fig. 2, which shows an expanded view of the ion anisotropies and fluxes from 0610 to 0640 UT. The magnetic field ordering of the anisotropies, as measured in the EPD scan plane, is clear. This ordering is indicative of a distribution of ions arriving at the spacecraft along field lines from the hemisphere containing Venus. Because few if any ions arrive from the opposite hemisphere, we associate these ion events with Venus and its interaction with the solar wind.

Figure 3 shows sample spectra at the time of the peak intensities observed during the EPD scan. Although the observed spectra vary somewhat throughout the encounter, their shapes are reasonably described by a power law of the form $J \approx E^{-\gamma}$, where E is energy, J is particle flux, and $3.5 \le \gamma \le 4$.

Mihalov and Barnes (*5*) reported observing a secondary peak of inferred O^+ fluxes in the several kiloelectron volt energy range. They attributed those ions to pickup of photodissociated O atoms (from the extended venusian atmosphere) by the shocked solar wind. More recently Moore *et al.* (*6*) presented observations from the Pioneer Venus Orbiter that they interpreted as suprathermal (4 to 6 keV) ions upstream of the venusian bow shock. Russell and Vaisberg (*7*) have presented synthesized spectra constructed with data from several Venera 10 orbits that show accelerated ions to 10 keV at the boundary of the venusian wake. Further, the Galileo plasma instrument observed ions up to ~10 keV at the time of the most intense events seen by the EPD (*4*).

Under the most favorable magnetic field orientation (perpendicular to the solar wind flow), the maximum energy expected for the pickup of a newly created ion by the interplanetary magnetic field is $2m_iV^2$, where V is the solar wind velocity and m_i is the mass of the ion. With the measured solar wind velocity of ~450 km/s (*4*), the maximum expected energy for an O^+ ion in these events would be ~65 keV, well below the maximum energies of up to 120 to 280 keV observed by the EPD. Further, during the observed ion events the interplanetary field had a substantial component parallel to the solar wind velocity, thereby reducing the expected maximum energies by one-half or more. Moreover, the ions observed by EPD arrived at Galileo from the antisolar hemisphere, in contrast to the expected solar wind direction for ion pickup. We conclude therefore that the ion pickup process is not the source of the observed ions.

Another possible ion source is the venusian bow shock, created by the interaction of the solar wind with the venusian atmosphere and ionosphere. Previous observations of upstream waves at Venus led Russell and Vaisberg (*7*) to suggest the possible existence of energetic ions in the venusian foreshock. To test this possibility, we have compared the Venus bow shock geometric calculations presented by Kivelson *et al.* (*3*) with the EPD observations. Figure 4 shows an expanded time plot of ion intensities together with bow shock parameters given in Kivelson *et al.* (*3*). Ion intensities are shown as counts per second and the energy coverage of the channels is indicated. The bow shock "depth" parameter, measured in Venus radii, R_V, is the distance from Galileo to a point directly upstream (or downstream) on the field line that is tangent to the bow shock. This distance is calculated with the observed field direction at the spacecraft and is positive when Galileo is downstream of the tangent field line. This parameter is taken to represent the depth of the spacecraft in the electron foreshock from



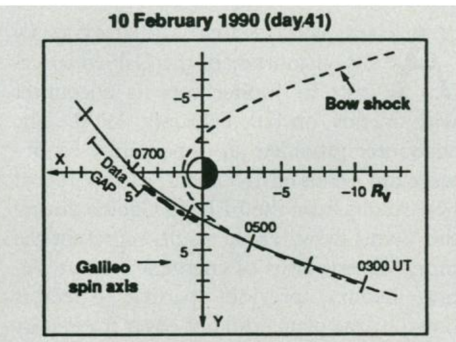


Fig. 1. EPD response during Venus flyby. Closest approach occurred at 0559:03 UT. The middle two color plots show spectrograms of ion [(**A**), log E increasing upwards] and electron [(**B**), log E increasing downwards] fluxes coded by the left scale of the color bar. Above and below these panels are anisotropy plots, normalized to lie between 0 and 1, for the lowest two EPD ion energy channels [(**C**), 42 to 65 keV; (**D**), 22 to 42 keV)]. The directions are referenced to the angular scan plan (perpendicular to the Galileo spin axis; 0° is toward the south ecliptic pole), and the relative magnitude is given by the right scale of the color bar. The anisotropy panels also show data points (white) giving the direction of the measured magnetic field in the scan plane. The plots above and below the anisotropy panels show the magnitude of the anisotropy as the log of the ratio of maximum to minimum intensities in the scan. For completeness, line plots of the channel count rates (CPS, counts per second) are also shown [(**E**), 120 to 280 keV; (**F**), 65 to 120 keV; (**G**), 42 to 65 keV; (**H**), 22 to 42 keV]. The flyby trajectory with the EPD energetic ion responses indicated by heavy dark bars is shown in the upper-right inset. No energetic particles were observed during any other data recording interval during the flyby.

the tangent field line. The "up" distance parameter is the distance along the tangent field line to the point directly upstream (or downstream) of Galileo. If this point is also upstream of the point of tangency, the distance is positive. The angle θ_{BN} is the angle between the shock normal and the interplanetary magnetic field calculated at the point where the projected field measured at Galileo intersects the shock.

Figure 4 shows that the energetic ion events observed by EPD correlate well with Galileo being located both in the foreshock region and a positive distance from the initial contact point during the events. Although the depth parameter barely becomes positive (or nearly zero) at the time of the 0546 to 0548 UT event, it does become less negative. This relative change is significant because, owing to the coarseness of the model, the absolute value of the parameters is not to be considered highly accurate (*8*). The figure also shows that the energetic ion events beginning at ~0547, 0601, and 0615 UT occur for θ_{BN} values ≥45°, whereas those beginning at ~0621, 0634, and 0638 UT occur for θ_{BN} values <45°.

We conclude from Fig. 4 that the observed energetic ions are associated with the Venus foreshock–bow shock region. Two possible processes operating within this region are capable of accelerating ions; these are Fermi acceleration [see, for example, Lee (*9*)] and shock-drift acceleration [see, for example, Decker (*10*)]. In the former process, ions generated or reflected by the shock and traveling sunward can be reflected numerous times between discontinuities and/or wave trains (propagating with the solar wind) and the bow shock. Under appropriate conditions, such as a magnetic field nearly parallel to the solar wind velocity, ion acceleration to >100 keV can occur. The resulting energetic ions are expected to have an exponential differential energy spectrum (*9*).

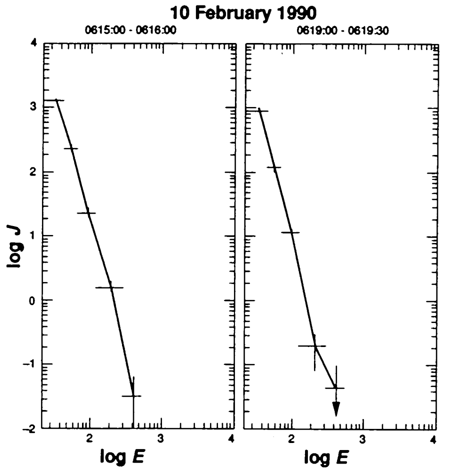


Fig. 3. Sample energetic ion spectra (in direction of peak fluxes) observed during flyby. Units of *E* are kiloelectron volts and those of *J* are cm^{-2} s^{-1} Sr^{-1} keV^{-1}.

Although magnetic field power spectra are observed to increase in intensity slightly during the ion events (*3*) in qualitative agreement with a Fermi process, the ion spectra are power law in shape and thus quantitatively disagree with the expectations of Fermi acceleration. Further, the magnetic field did not consistently have the near-parallel orientation with the solar wind velocity vector required for Fermi acceleration of ions to the energies observed. This angle ranged from ~10° to ~60° for the energetic ion events measured by Galileo. In addition, the observed ion anisotropies indicate few if any ions arriving from the sunward hemisphere. Thus, the acceleration process must have existed between the spacecraft and the foreshock–bow shock region. Thus, for a Fermi acceleration process all the reflecting or scattering and acceleration must occur between Galileo and the bow shock, and EPD then observes a leakage traveling upstream from the interaction region. The sum of these considerations and constraints leads us to conclude that Fermi acceleration was

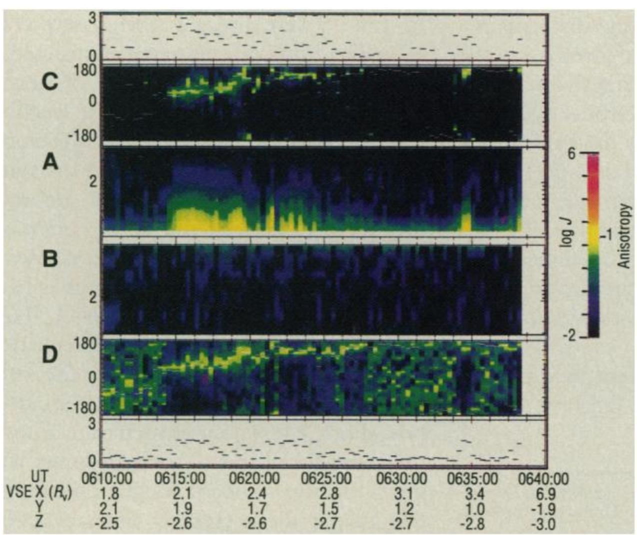


Fig. 2. Expanded plot of EPD response showing a high degree of alignment in measured anisotropies and magnetic field direction in the scan plane (labeled as in Fig. 1).

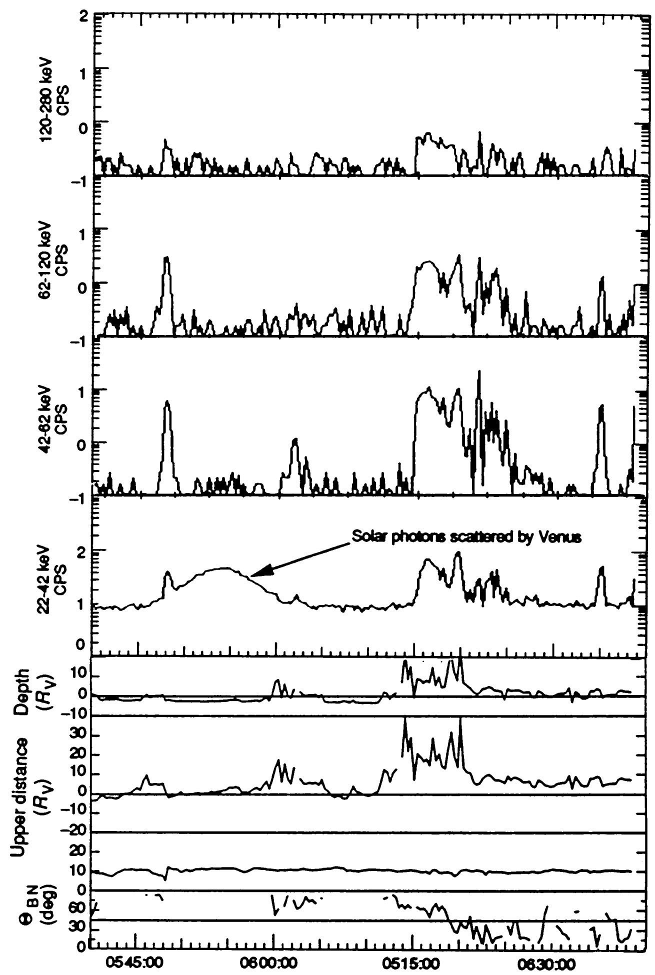


Fig. 4. Comparison of EPD response with bow shock calculations presented by Kivelson *et al.* (*3*). Energetic ions appear for all values of θ_{BN} observed. See text for discussion.

not the dominant mechanism responsible for the observed energetic ions.

The shock-drift acceleration process energizes ions by magnetically driven drift along the shock electric field. Decker (*10*) showed that under appropriate conditions and particle trajectory geometries ions can be accelerated to energies that are up to two orders of magnitude higher than the "seed" population. If one assumes that the observations of several kiloelectron volt ions at Venus (*5, 6, 7*) could represent a "seed" population for the shock-drift acceleration process, the present observations of energetic ions into the 120- to 280-keV energy range can qualitatively be explained. However, a unique aspect of the geometry at Venus is that the ion energies observed have gyroradii of 1/4 to 1 R_V (H^+) or ~1 to 4 R_V (O^+). These sizes are of the order of or larger than the subsolar shock radius and imply that the subsolar shock region is not the site of the observed ion energization. In fact, the field geometry during the ion events indicates that the field line through Galileo intersected the shock a considerable distance downstream of the subsolar region.

Although shock-drift acceleration appears to be the most promising explanation of the EPD observations at this time, it is not clear whether the seed population is the solar wind or planetary pickup ions. A more detailed analysis of the data coupled with model calculations should clarify this issue.

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11. We especially acknowledge the major contributions of three EPD team members who did not live to see the results of their efforts: Wolfgang Stüdemann, James Cessna, and Eric Bubla. These three talented people were positive influences not only on the EPD team but also on all who were fortunate enough to know them. We dedicate this paper to their memory. The successful construction, test, and launch of the EPD has required the continuing efforts of many dedicated professionals. We thank those many people who had major or continuing responsibilities in the EPD effort or both. The following major contributors, exclusive of the authors of the present paper, are listed with the organizational affiliation existing at the time of their association with EPD: J. Crawford, J. Dassoulas, D. Fort, S. Gary, J. Heiss, B. J. Hook, J. Kohl, H. Malcolm, R. Moore, T. Mueller, M. Puritz, S. Purwin, N. Rothman, P. Schwartz, R. Thompson, J. Townsend, Jr., C. Wingate, and H. Wong, from The Johns Hopkins University Applied Physics Laboratory; W. Boeker, W. Klemme, H. Sommer, W. Weiss, and H. Wirbs, from the Max Planck Institute für Aeronomie; R. Dayhoff and C. Holmes, from the National Oceanic and Atmospheric Administration Space Environment Laboratory; W. Fawcett, R. Gibbs, G. McSmith, R. Parrish, J. Taylor, and J. Willett, from the Jet Propulsion Laboratory; S. Brown from Goddard Space Flight Center; and J. Burke and R. Martin, contract employees. We thank M. G. Kivelson and the Galileo magnetometer team for use of their magnetometer data in our display and analysis of EPD data. This work was supported by a National Aeronautics and Space Administration contract to The Johns Hopkins University Applied Physics Laboratory under the Department of Navy Task IAYX910X; contract N00039-89-C-0001.

26 April 1991; accepted 1 July 1991

Plasma Observations at Venus with Galileo

L. A. Frank, W. R. Paterson, K. L. Ackerson, F. V. Coroniti, V. M. Vasyliunas

Plasma measurements were obtained with the Galileo spacecraft during an approximately 3.5-hour interval in the vicinity of Venus on 10 February 1990. Several crossings of the bow shock in the local dawn sector were recorded before the spacecraft passed into the solar wind upstream from this planet. Although observations of ions of the solar wind and the postshock magnetosheath plasmas were not possible owing to the presence of a sunshade for thermal protection of the instrument, solar wind densities and bulk speeds were determined from the electron velocity distributions. A magnetic field–aligned distribution of hotter electrons or "strahl" was also found in the solar wind. Ions streaming into the solar wind from the bow shock were detected. Electron heating at the bow shock, ≤20%, was notably small, with substantial density increases by factors of 2 to 3 at the day side of the shock that decrease for shock crossings further downstream from the planet. A search for pickup ions from the hot hydrogen and oxygen planetary coronas yielded an upper limit for these densities in the range of 10^{-3} ion per cubic centimeter, which is consistent with densities expected from current models of neutral gas densities.

Our current knowledge of the interaction of the solar wind with the planet Venus has been provided by a series of Mariner and Venera spacecraft and by Pioneer Venus Orbiter (*1*). The solar wind interacts directly with the planet's ionosphere and atmosphere, and thus the interaction is more similar to the situation for a comet than that of Earth, for which the solar wind is held off by our planet's magnetic field. Measurements have established that a bow shock exists at Venus and that a plasma cavity in the solar wind is formed on the dark side of the planet. Extensive observations with Pioneer Venus Orbiter provide a basis for understanding the mechanisms for the deflection of solar wind flow on the day side of the planet: at low dynamic pressures in the solar wind a magnetic barrier forms above the ionosphere, and at higher pressures ionospheric currents are driven by the induction electric field provided by the solar wind.

Electrostatic analyzers were used to provide plasma measurements over the energy per unit charge (E/Q) range of 0.8 V to 52 kV (*2*). A record of the instrument responses during the flyby of Venus is shown in the energy-time spectrograms (*3*) of Fig. 1 for two sets of sensors, E2, P2 and E6, P6. The spacecraft trajectory provided plasma measurements along the dawn flank of the bow shock and subsequently within the upstream solar wind (*4*) (see also Fig. 2). The plasma instrument was operated during the period 0318 to 0638 universal time (UT). Sensors E6 and P6 were directed most closely to the solar direction without being obstructed by the sunshade, whereas the fields of view of E2 and P2 allowed detection of electrons and positive ions, respectively, with velocity vectors directed generally toward the sun.

Crossings of the bow shock are most readily identified in the spectrogram for sensor E2 by the increases and decreases of low-energy electrons with energies ~10 to 100 eV, for example, at 0447, 0441, 0438, and 0422 UT. The regions of enhanced electron intensities occurred when the spacecraft entered the magnetosheath behind the bow shock. More accurate determinations of the times for all bow shock crossings were given by the onboard magnetometer (*5*). We list the above crossing times in reverse chronological order because in the spectrogram the electron signatures of bow shock crossings become weaker with downstream

L. A. Frank, W. R. Paterson, K. L. Ackerson, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.
F. V. Coroniti, Departments of Physics and Astronomy, University of California, Los Angeles, CA 90024.
V. M. Vasyliunas, Max-Planck-Institut für Aeronomie, Postfach 20, W-3411 Katlenburg-Lindau, Germany.